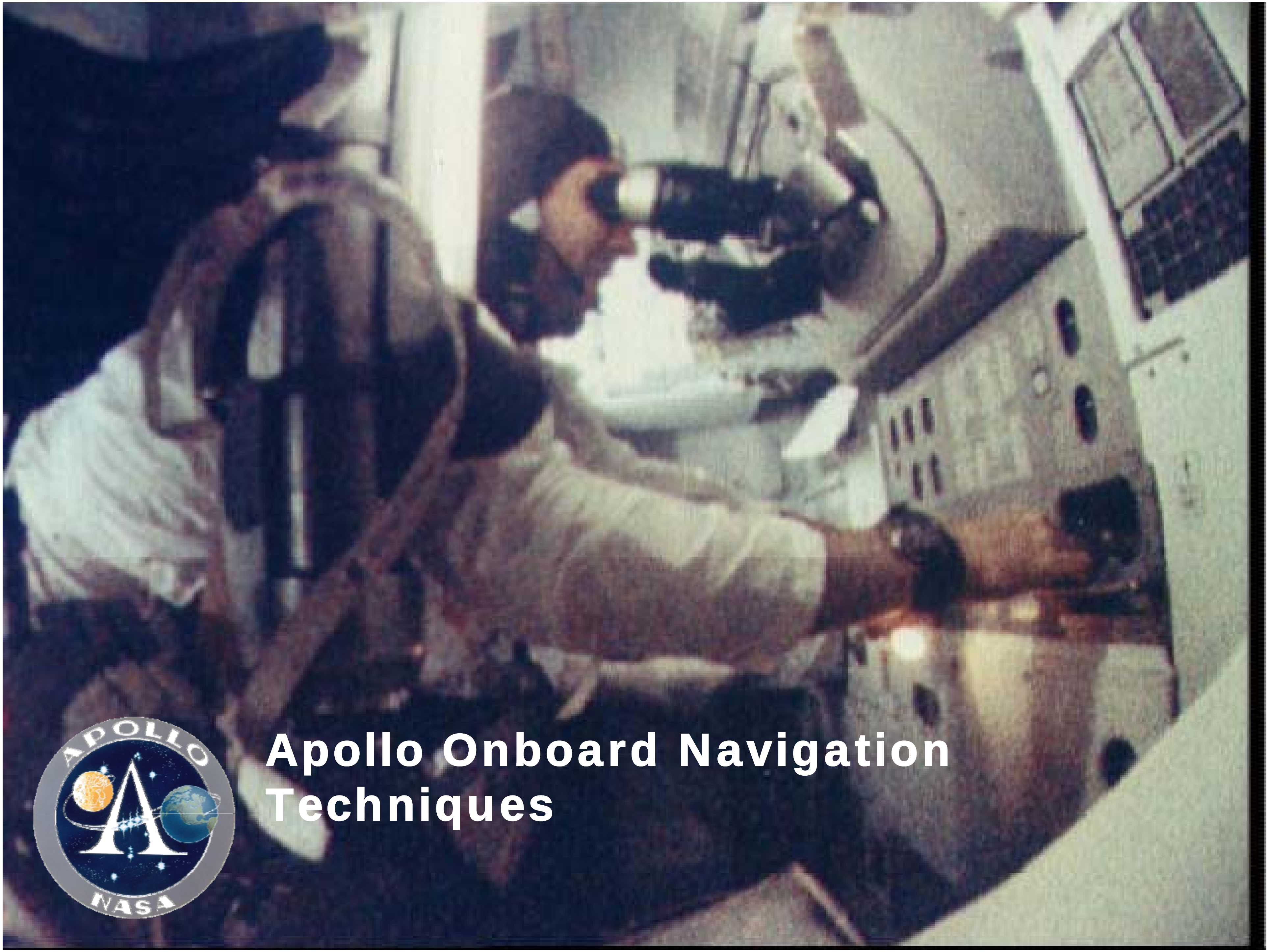
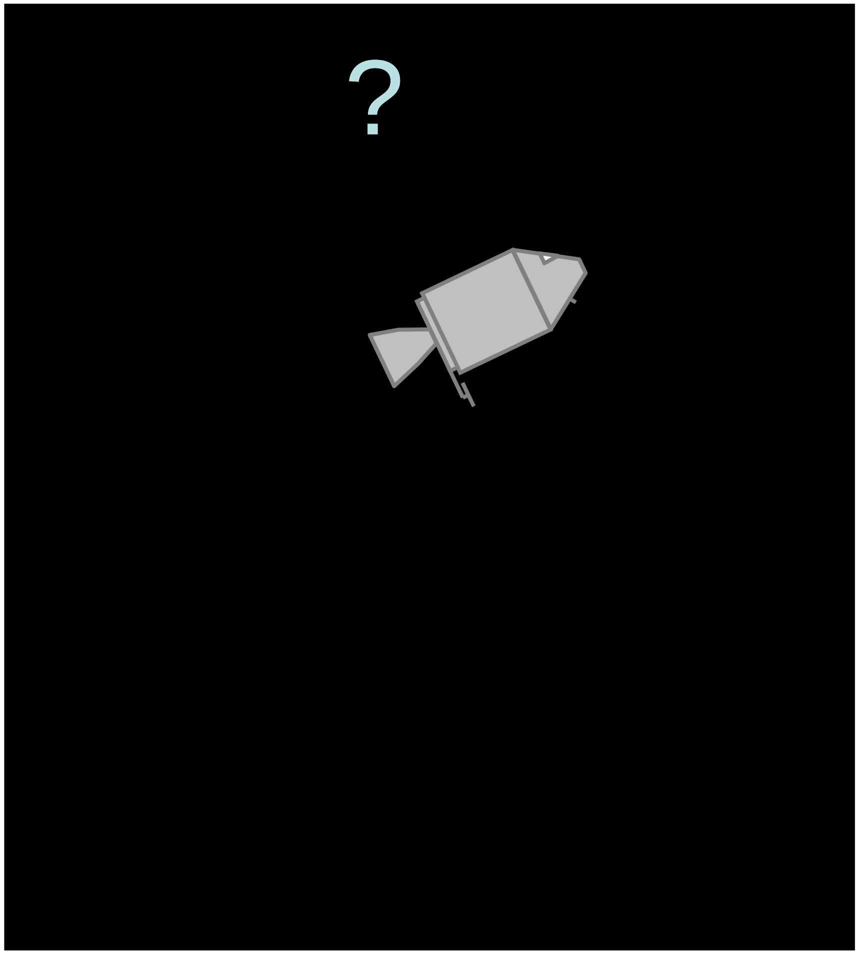

APOLLO
NASA
Apollo Onboard Navigation
Techniques

Objectives

- Review basic navigation concepts
- Describe coordinate systems
- Identify attitude determination techniques
  - Prime: PGNCS IMU Management
  - Backup: CSM SCS/LM AGS Attitude Management
- Identify state vector determination techniques
  - Prime: PGNCS Coasting Flight Navigation
  - Prime: PGNCS Powered Flight Navigation
  - Backup: LM AGS Navigation

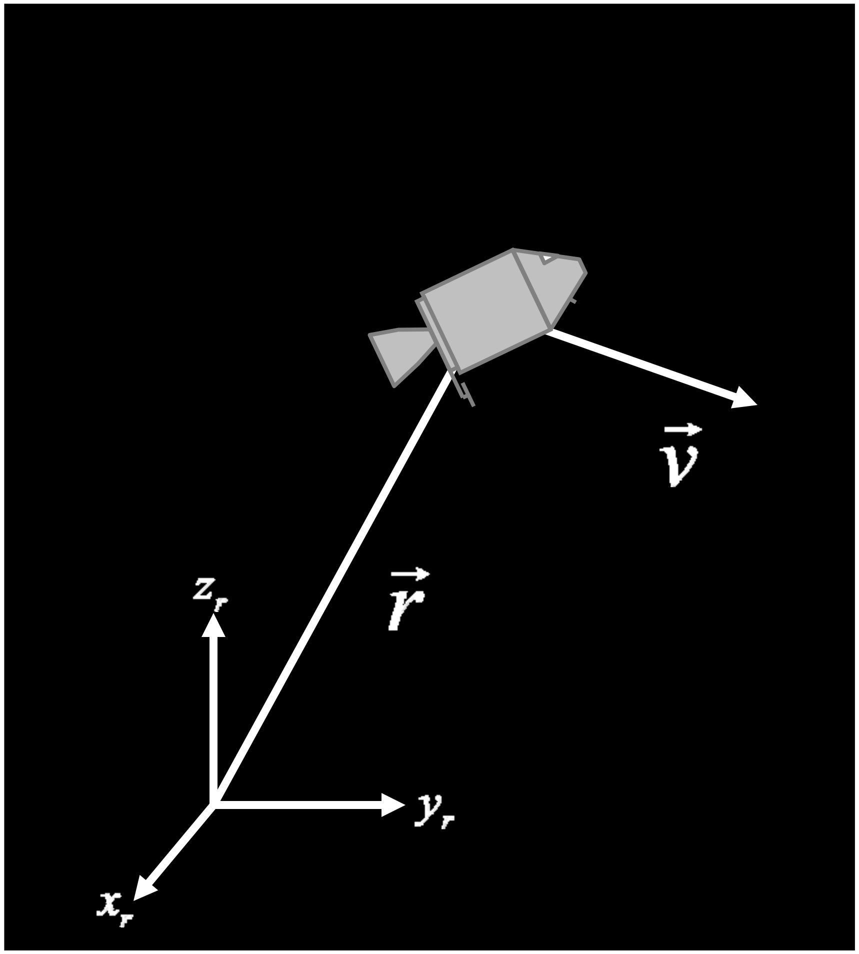
Review of Basic Navigation Concepts

- Navigation: “Where am I?”



Review of Basic Navigation Concepts

- Navigation: "Where am I?"
- Vehicle maintains internal representation of where it is with respect to some external reference (coordinate system)
  – State vector (position and velocity vectors)



Review of Basic Navigation Concepts

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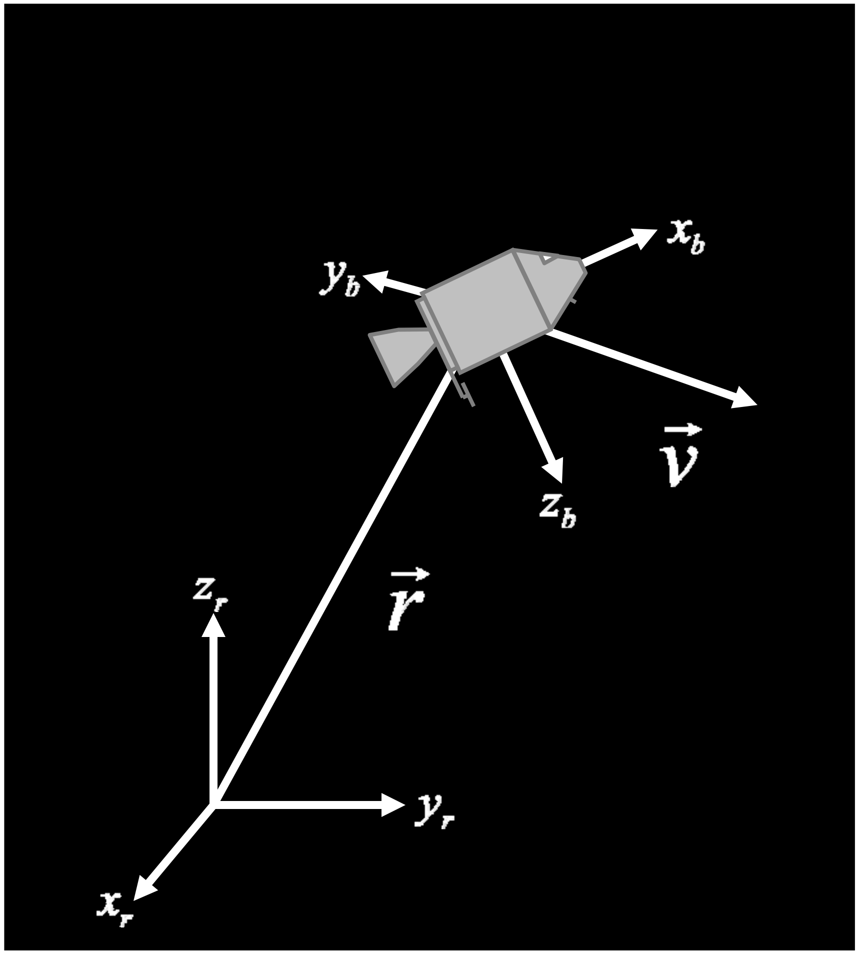
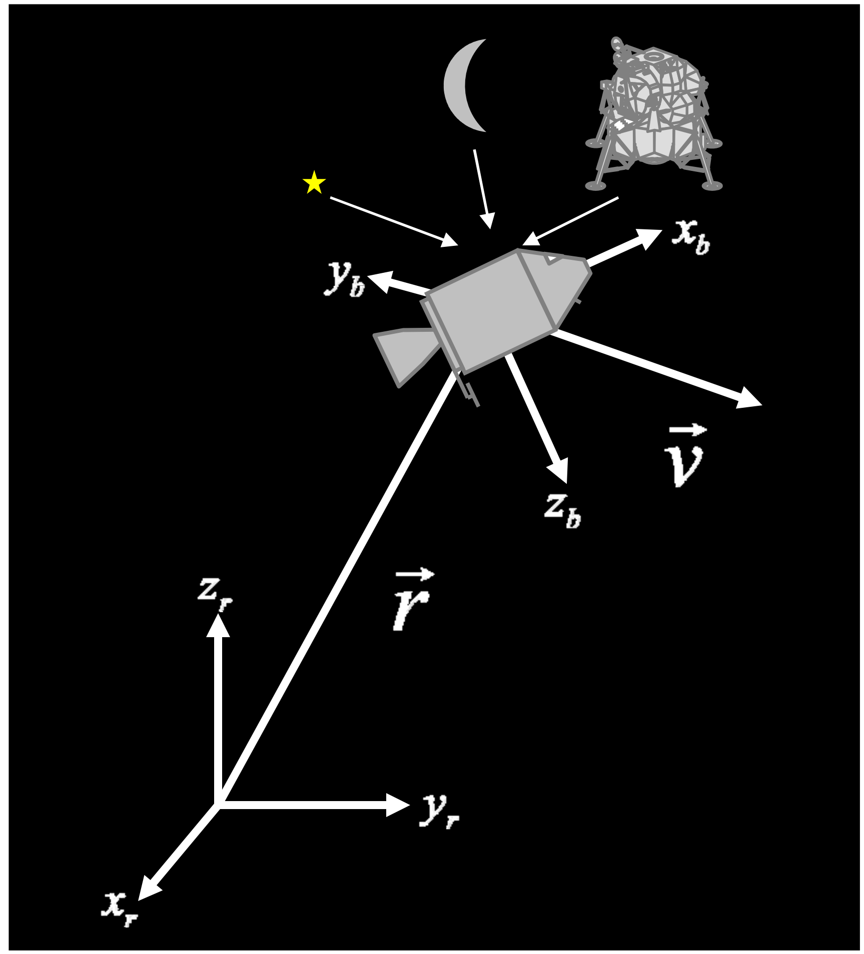
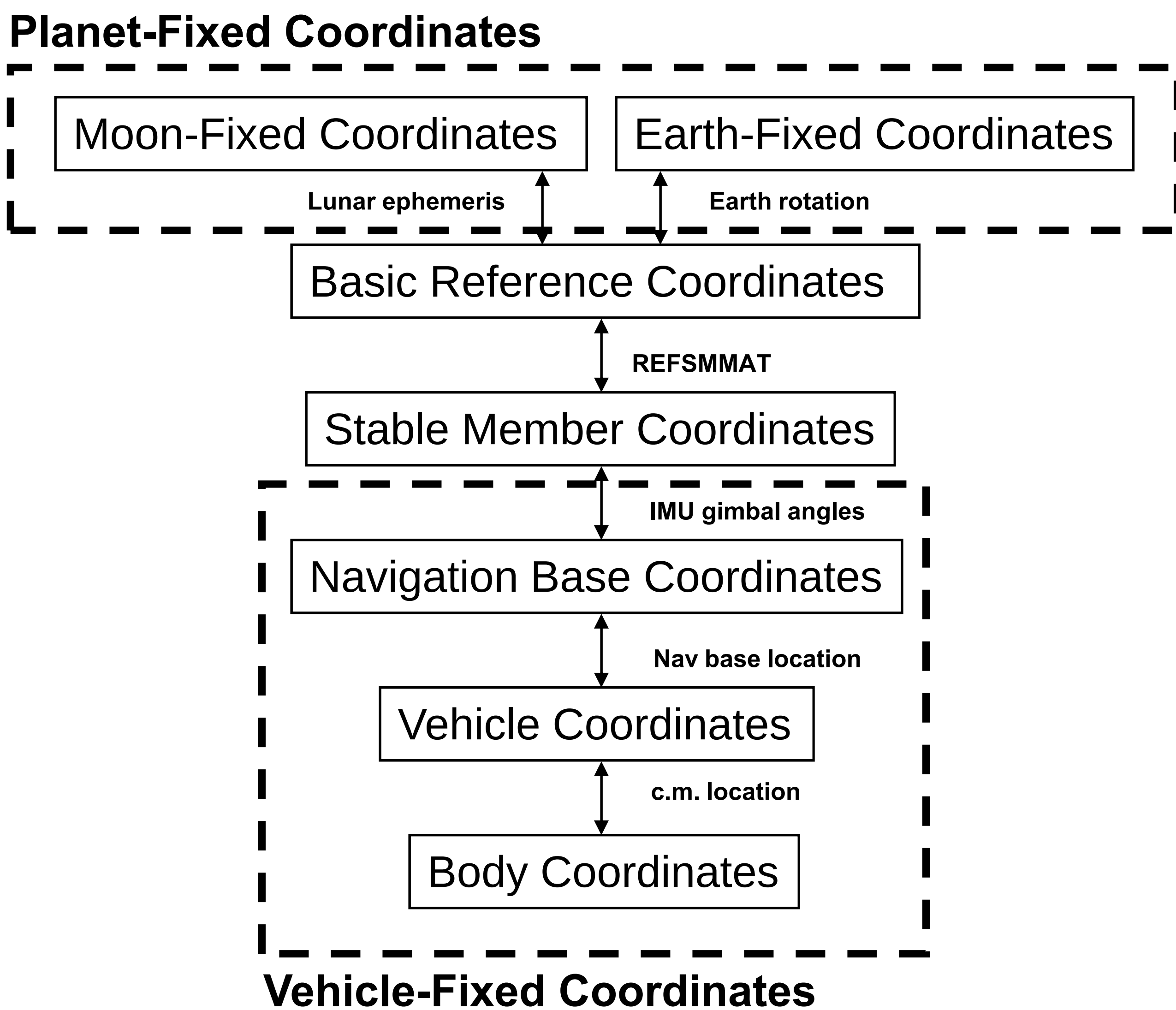


Review of Basic Navigation Concepts

- Navigation: "Where am I?"
- Vehicle maintains internal representation of where it is with respect to some external reference (coordinate system)
  - State vector (position and velocity vectors)
  - Attitude
- To maintain accuracy, this internal representation must be updated periodically using some source of external "truth data" (sensor measurements)



Coordinate Systems

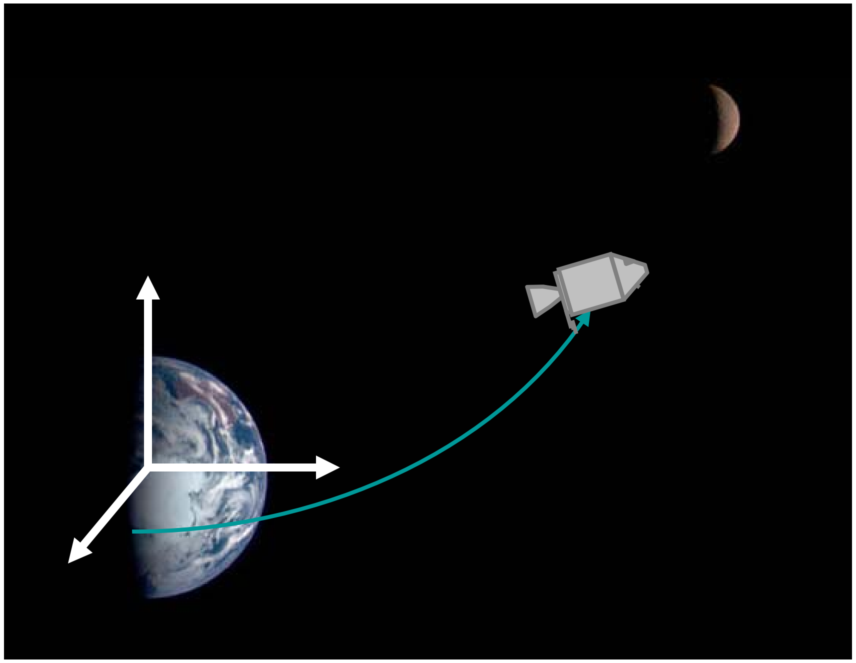


Basic Reference Coordinate System

- Inertial coordinate system
  - All nav stars and lunar/solar ephemerides were referenced to this system
  - All vehicle state vectors referenced to this system except during Lunar Module (LM) powered flight
- Epoch at nearest beginning of year
  - Simplified inertial-to-Earth-fixed computations

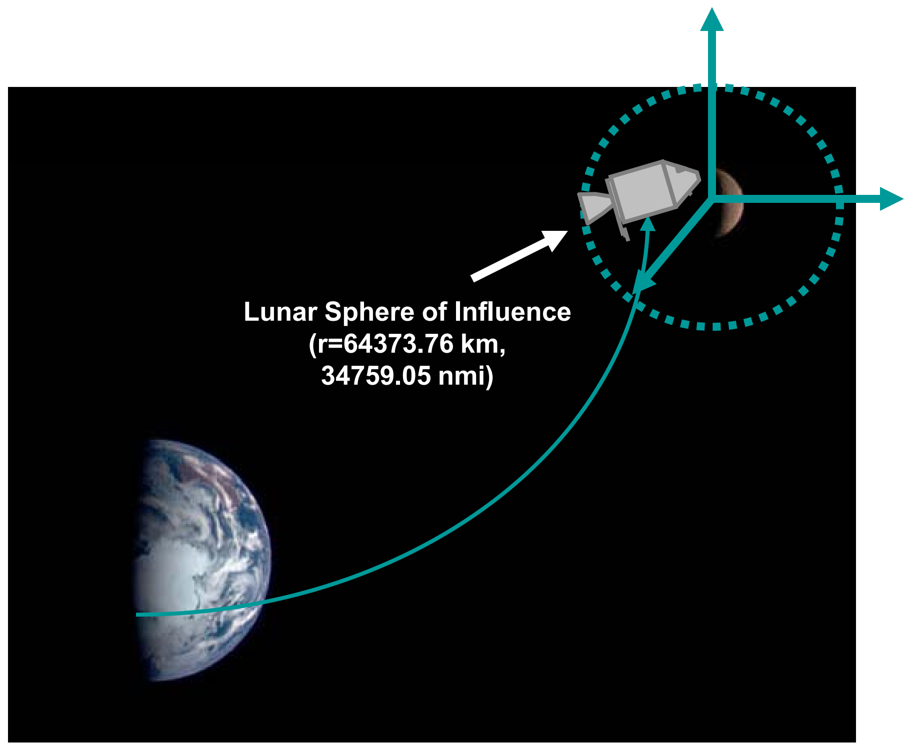
Basic Reference Coordinate System

- Origin at center of Earth or center of moon



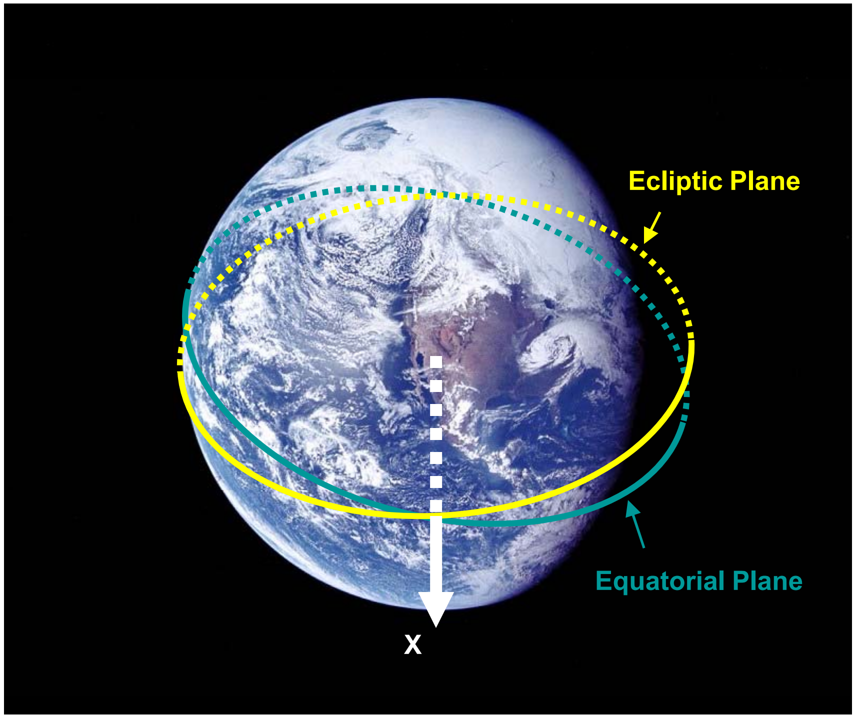
Basic Reference Coordinate System

- Origin at center of Earth or center of moon
  - Command and Service Module (CSM) navigation automatically transformed between Earth and moon centered when crossing the moon's Sphere of Influence (SOI)



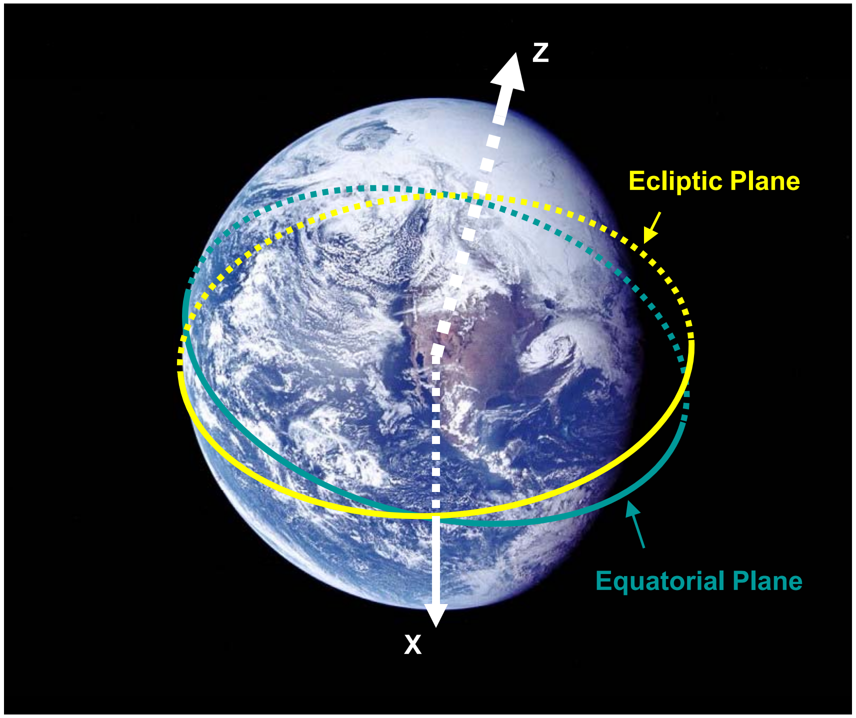
Basic Reference Coordinate System

- Origin at center of Earth or center of moon
  - Command and Service Module (CSM) navigation automatically transformed between Earth and moon centered when crossing the moon's Sphere of Influence (SOI)
- Axes:
  - X-axis pointed to First Point of Aries



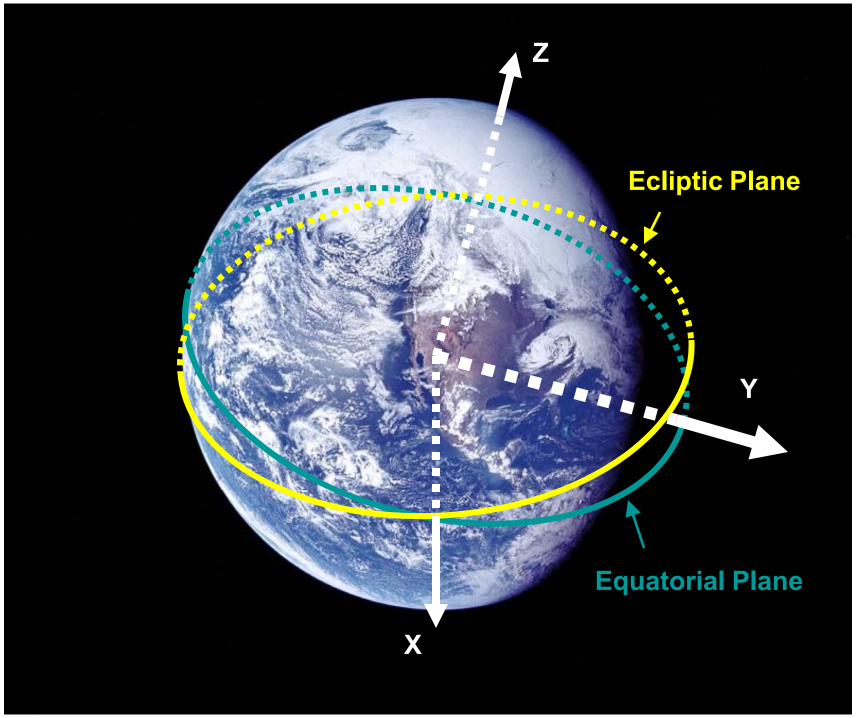
Basic Reference Coordinate System

- Origin at center of Earth or center of moon
  - Command and Service Module (CSM) navigation automatically transforms between Earth and moon centered when crossing the moon's Sphere of Influence (SOI)
- Axes:
  - X-axis pointed to First Point of Aries
  - Z axis parallel to Earth mean north pole



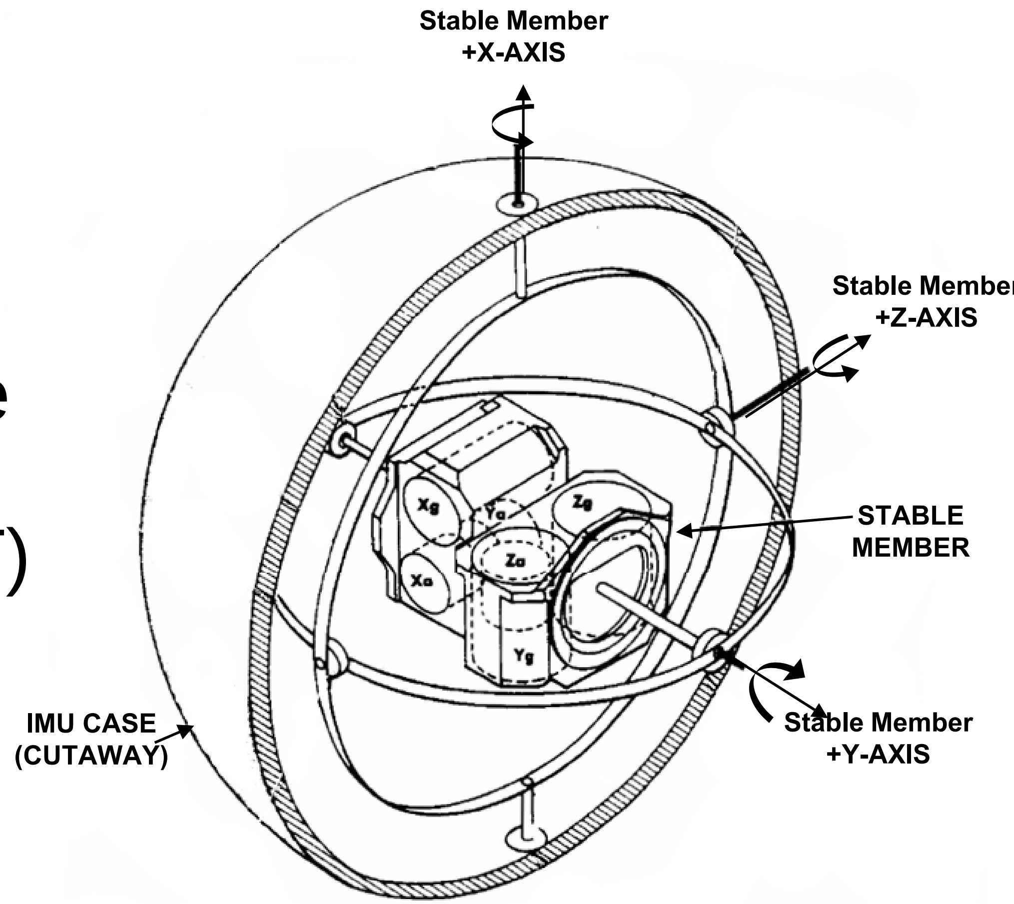
Basic Reference Coordinate System

- Origin at center of Earth or center of moon
  - Command and Service Module (CSM) navigation automatically transforms between Earth and moon centered when crossing the moon's Sphere of Influence (SOI)
- Axes:
  - X-axis pointed to First Point of Aries
  - Z axis parallel to Earth mean north pole
  - Y axis completed right-handed system



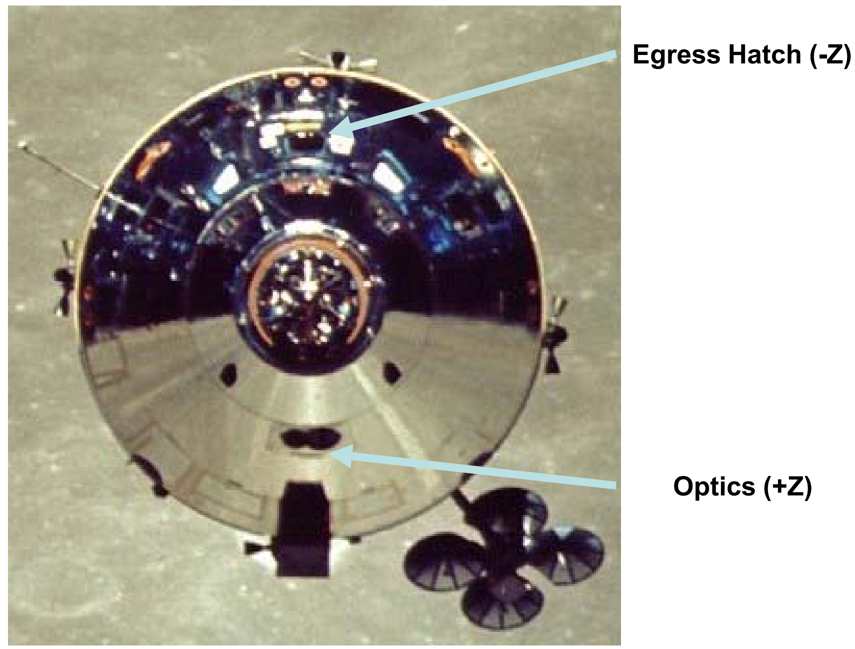
IMU Stable Member Coordinate System

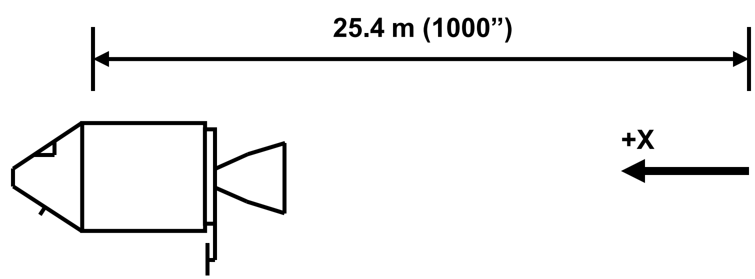
- Inertial coordinate system
- Defined relative to BRCS by REFerence to Stable Member MATrix (REFSMMAT)
- Many possible alignments during a mission (discussed later)



CSM Vehicle Coordinate System

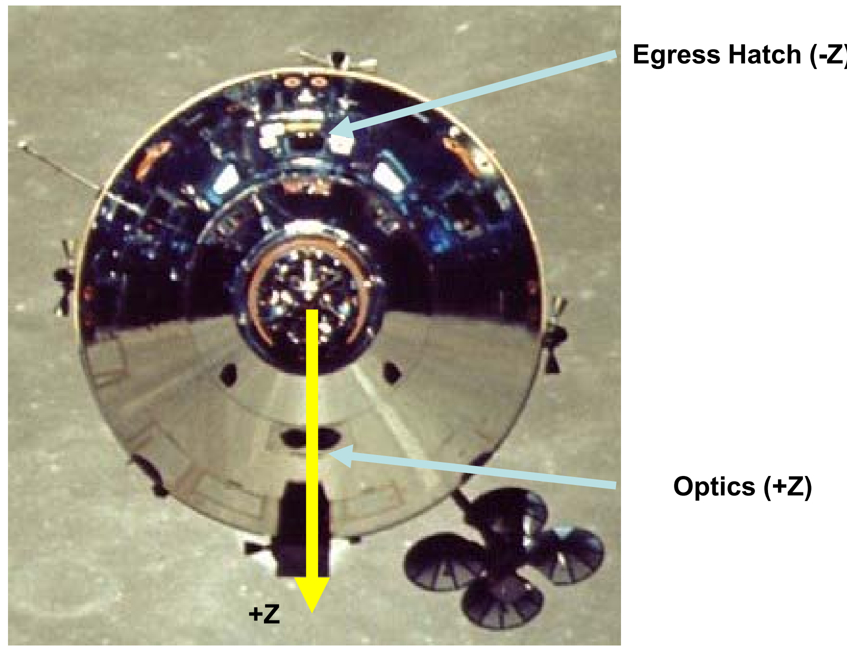
- Rotating coordinate system, fixed to CSM body
- Origin along vehicle centerline, 25.4 m (1000 in) behind Command Module (CM) heat shield
- Axes:
  - +X "forward" along longitudinal axis

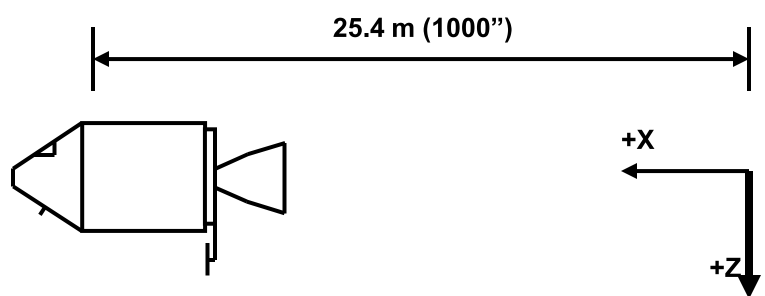




CSM Vehicle Coordinate System

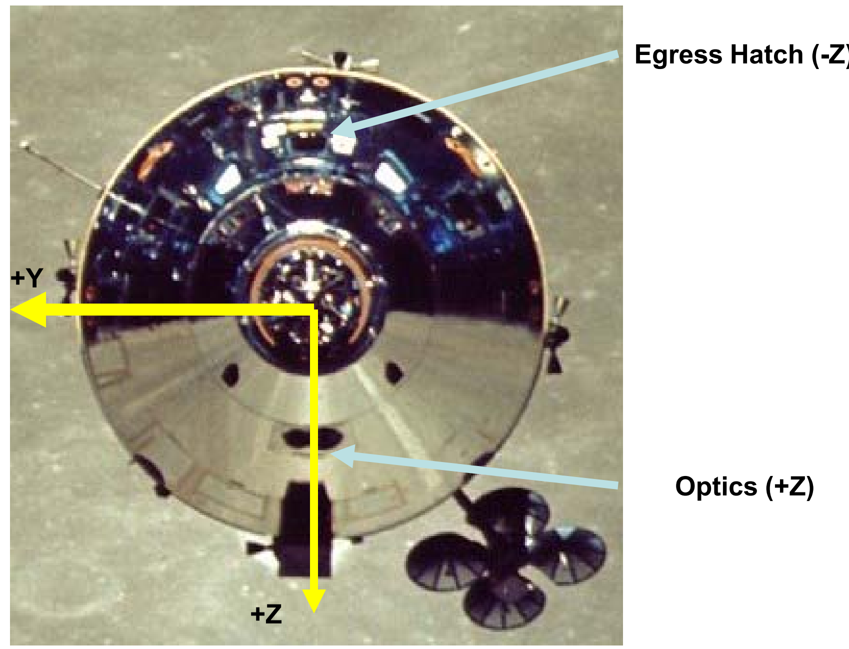
- Rotating coordinate system, fixed to CSM body
- Origin along vehicle centerline, 25.4 m (1000 in) behind Command Module (CM) heat shield
- Axes:
  - +X "forward" along longitudinal axis
  - +Z "down" along crew's feet when in couches

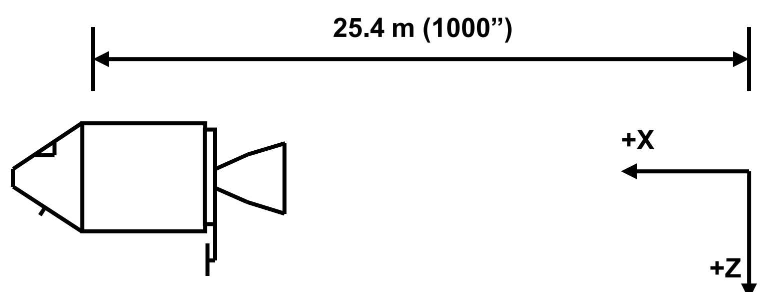




CSM Vehicle Coordinate System

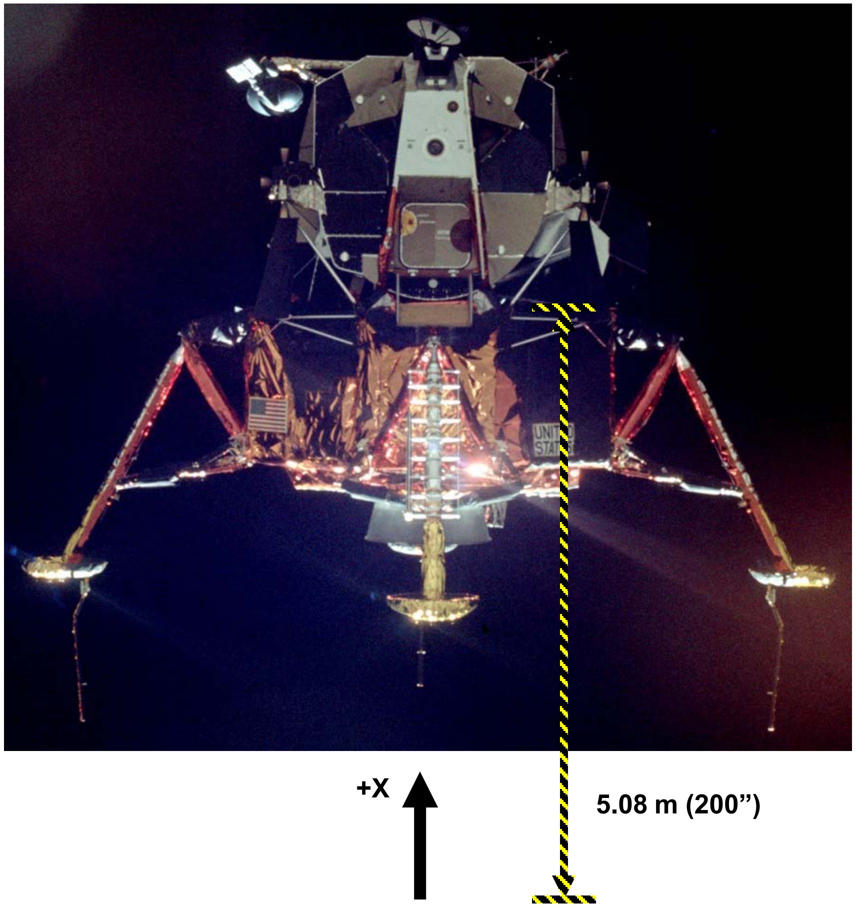
- Rotating coordinate system, fixed to CSM body
- Origin along vehicle centerline, 25.4 m (1000 in) behind Command Module (CM) heat shield
- Axes:
  - +X “forward” along longitudinal axis
  - +Z “down” along crew’s feet when in couches
  - +Y “starboard” completed right-handed system





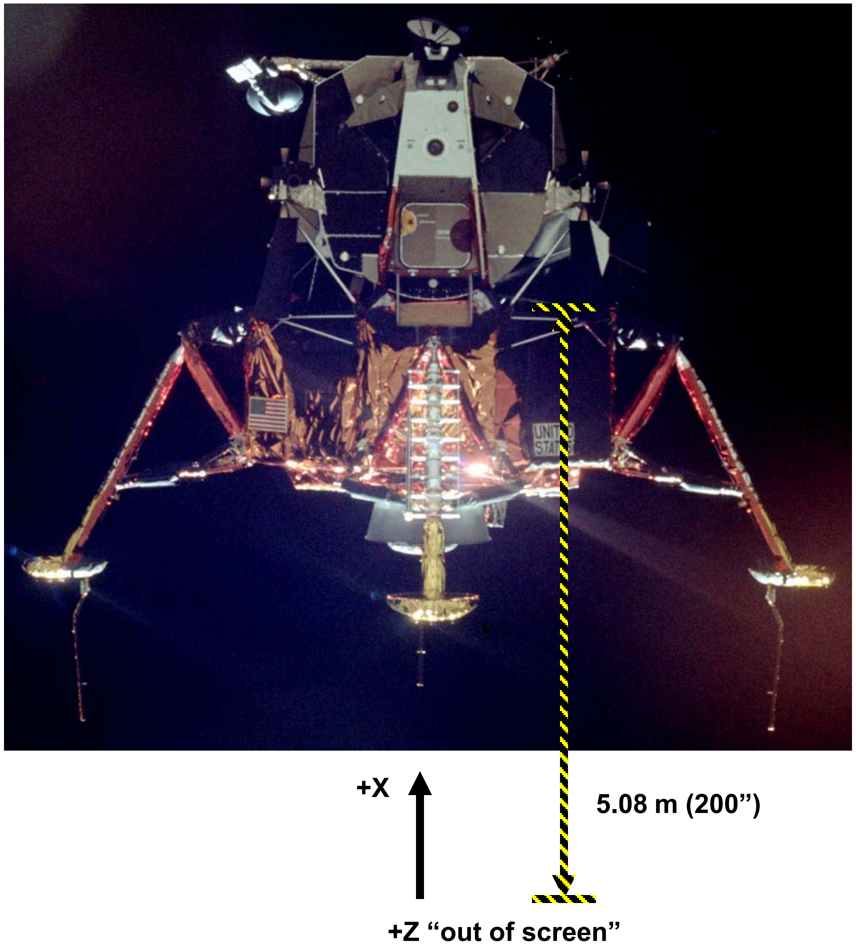
LM Vehicle Coordinate System

- Rotating coordinate system, fixed to LM body
- Origin along vehicle centerline, 5.08 m (200 in) below LM ascent stage base
- Axes:
  – +X “up” through top hatch



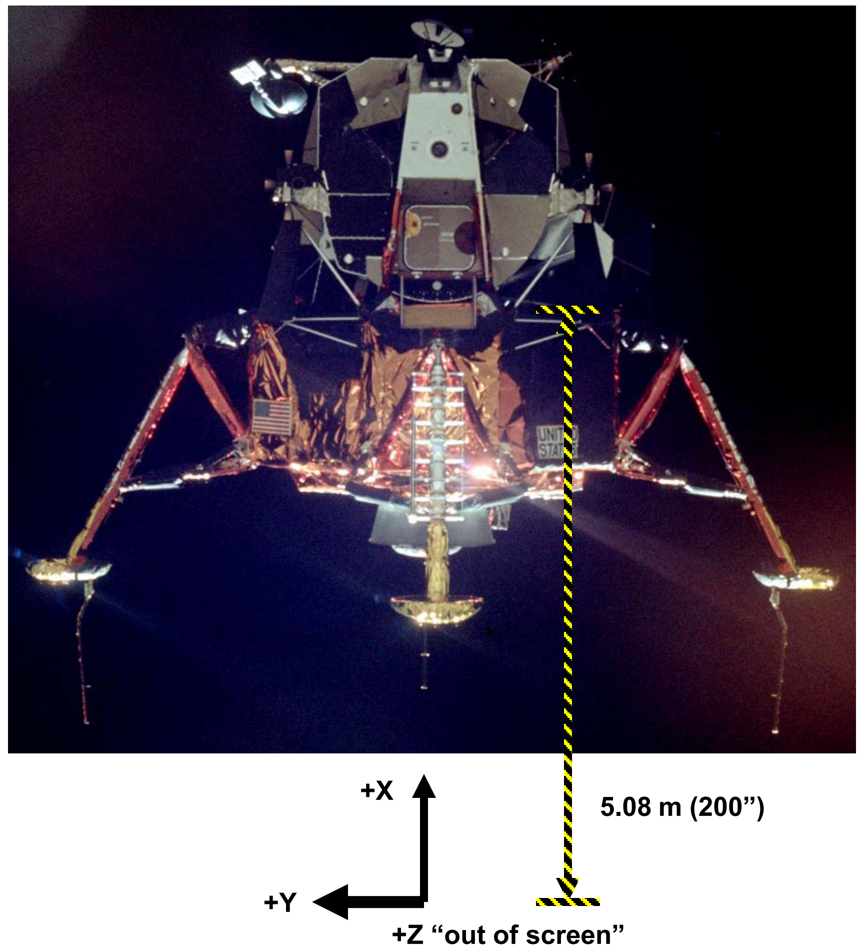
LM Vehicle Coordinate System

- Rotating coordinate system, fixed to LM body
- Origin along vehicle centerline, 5.08 m (200 in) below LM ascent stage base
- Axes:
  - +X "up" through top hatch
  - +Z "forward" through egress hatch



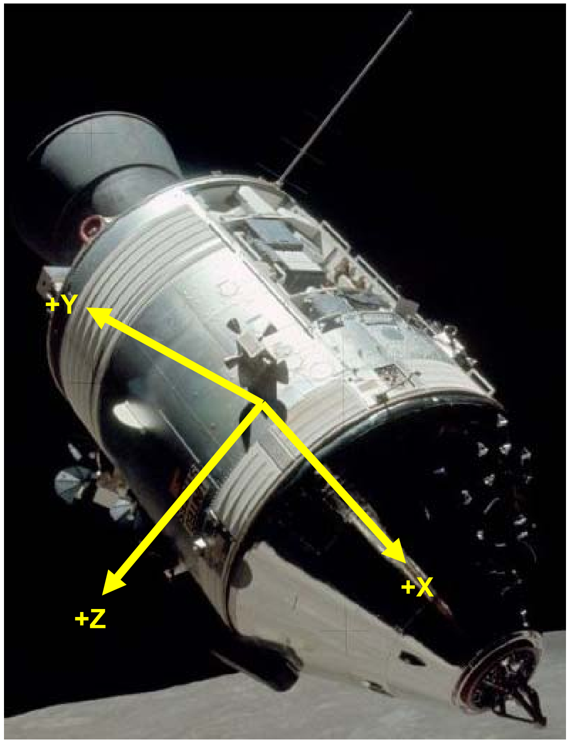
LM Vehicle Coordinate System

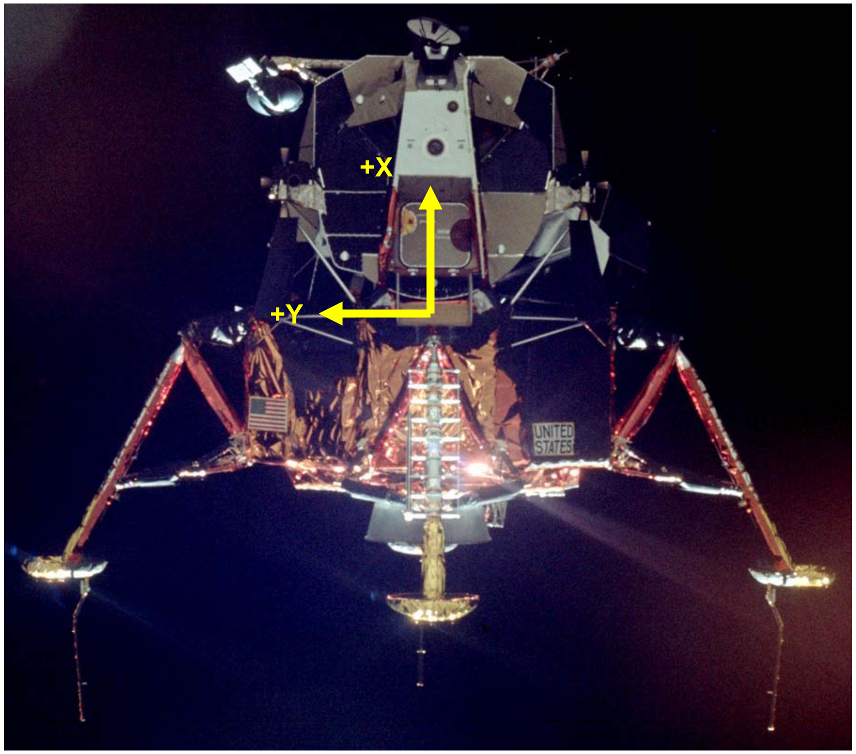
- Rotating coordinate system, fixed to LM body
- Origin along vehicle centerline, 5.08 m (200 in) below LM ascent stage base
- Axes:
  - +X "up" through top hatch
  - +Z "forward" through egress hatch
  - +Y "starboard" completed right-handed system



CSM / LM Body Coordinate Systems

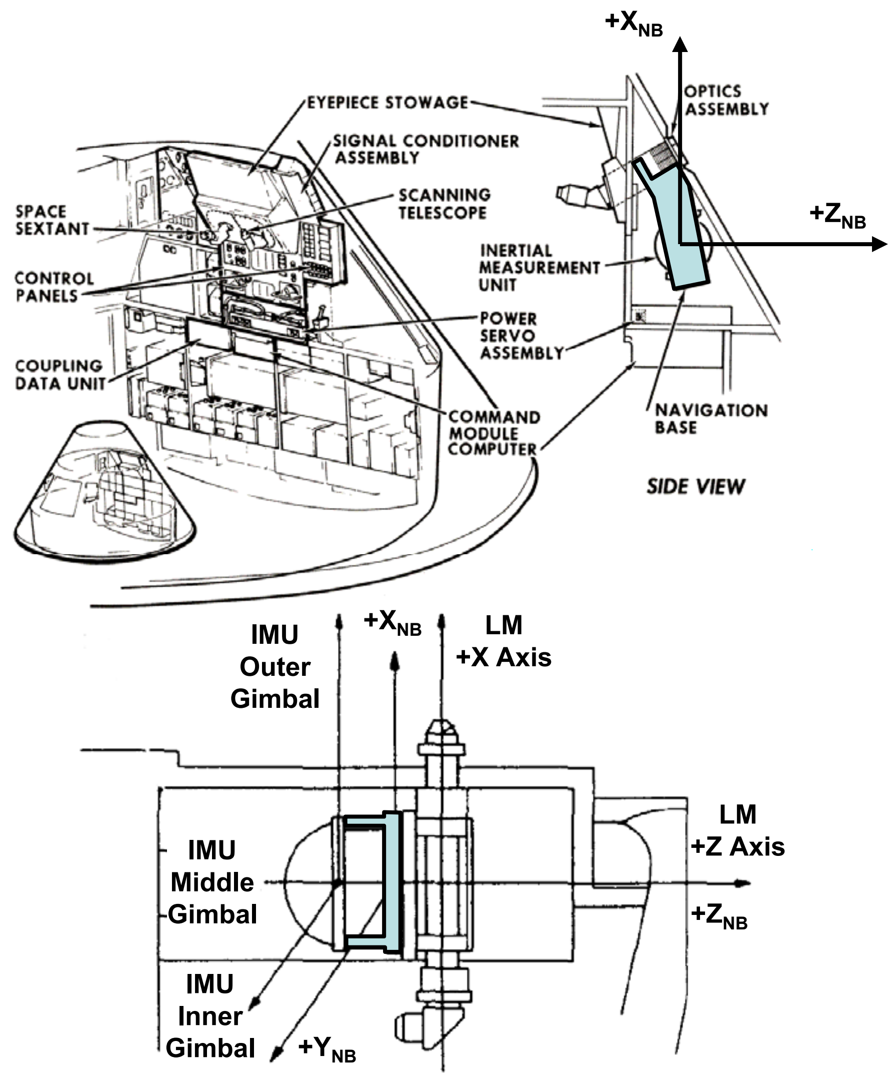
- Axes parallel to vehicle coordinate system
- Origin at vehicle center of mass





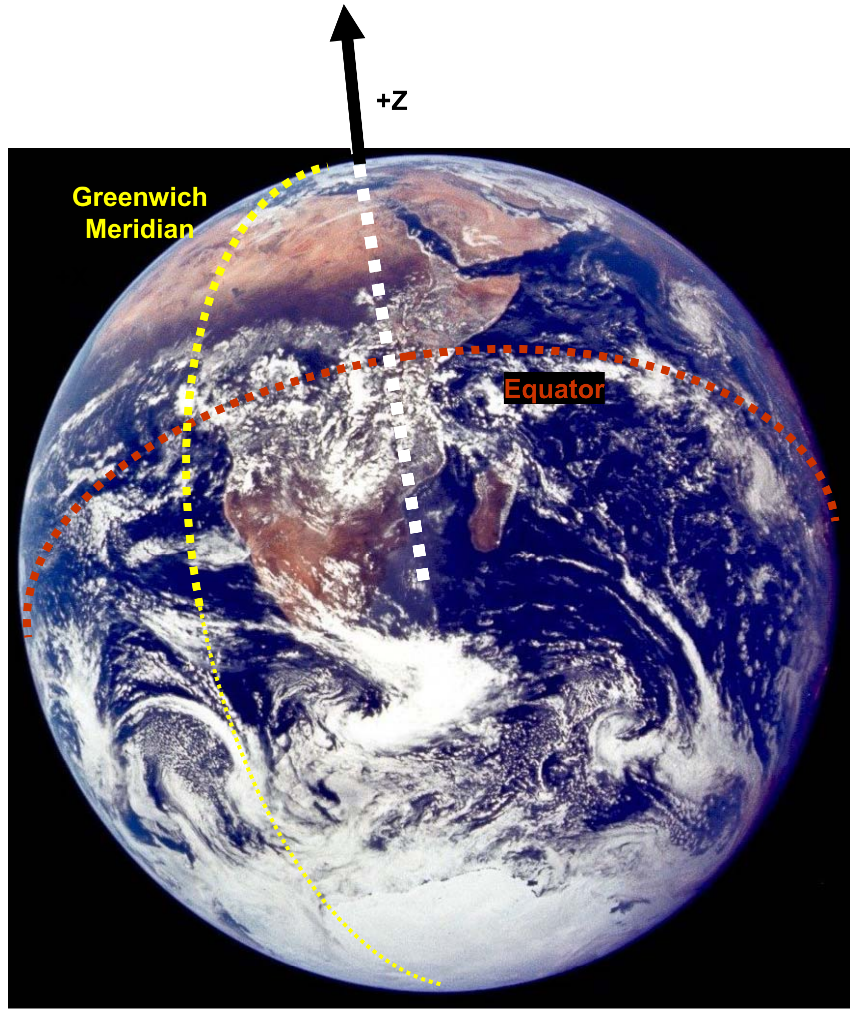
Navigation Base Coordinate System

- Rotating coordinate system, fixed to navigation base
  - IMU gimbal angles define the transformation between stable member coordinates and nav base coordinates
- Origin at center of navigation base
- Axes parallel to vehicle body axes



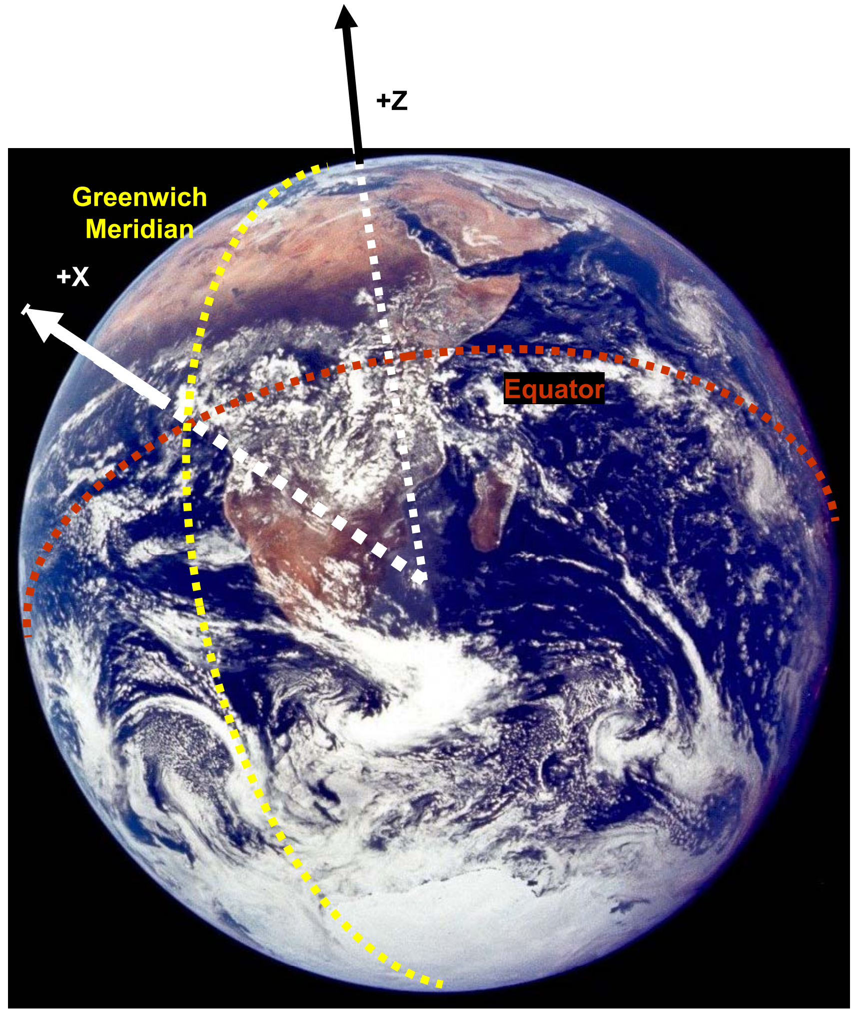
Earth-fixed Coordinate System

- Rotating coordinate system, fixed to Earth
  - All Earth landmarks, including launch site vector, referenced to this system
- Origin at center of Earth
- Axes:
  - +Z along true north pole



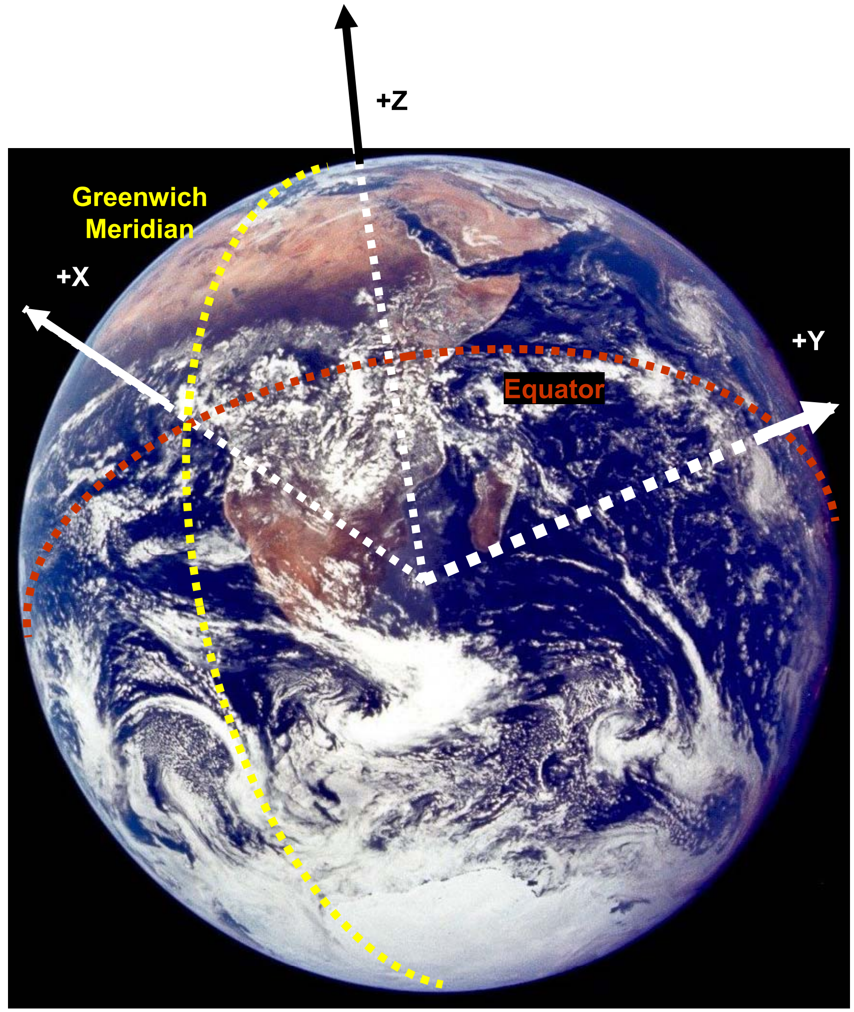
Earth-fixed Coordinate System

- Rotating coordinate system, fixed to Earth
  - All Earth landmarks, including launch site vector, referenced to this system
- Origin at center of Earth
- Axes:
  - +Z along true north pole
  - +X along true Greenwich meridian at equator



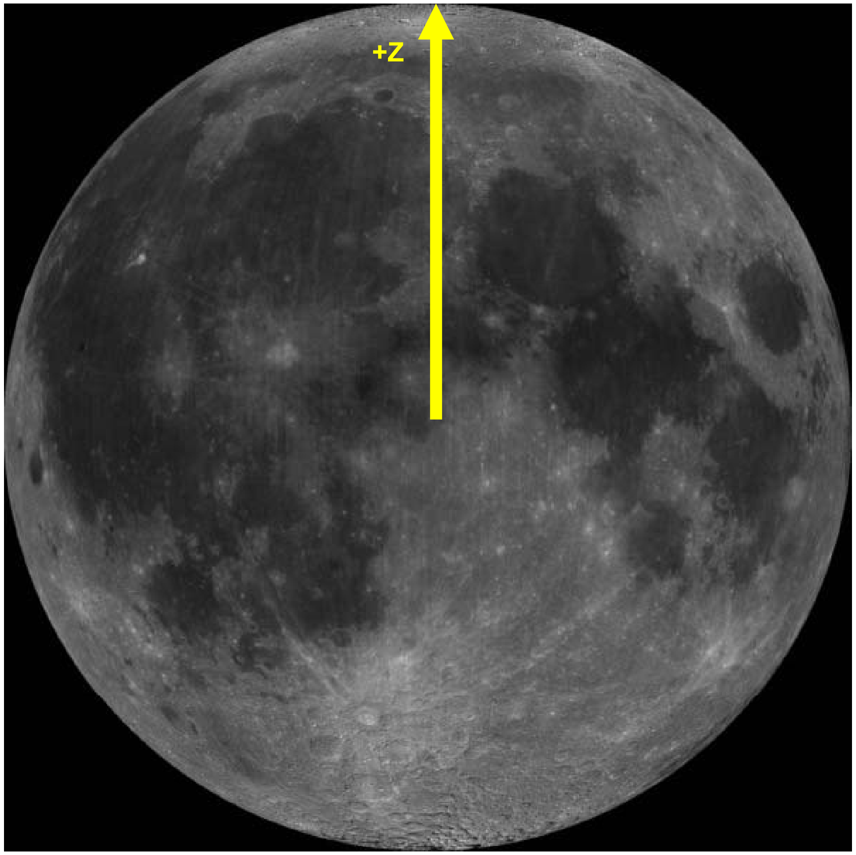
Earth-fixed Coordinate System

- Rotating coordinate system, fixed to Earth
  - All Earth landmarks, including launch site vector, referenced to this system
- Origin at center of Earth
- Axes:
  - +Z along true north pole
  - +X along true Greenwich meridian at equator
  - +Y in equatorial plane, completed right-handed system



Moon-fixed Coordinate System

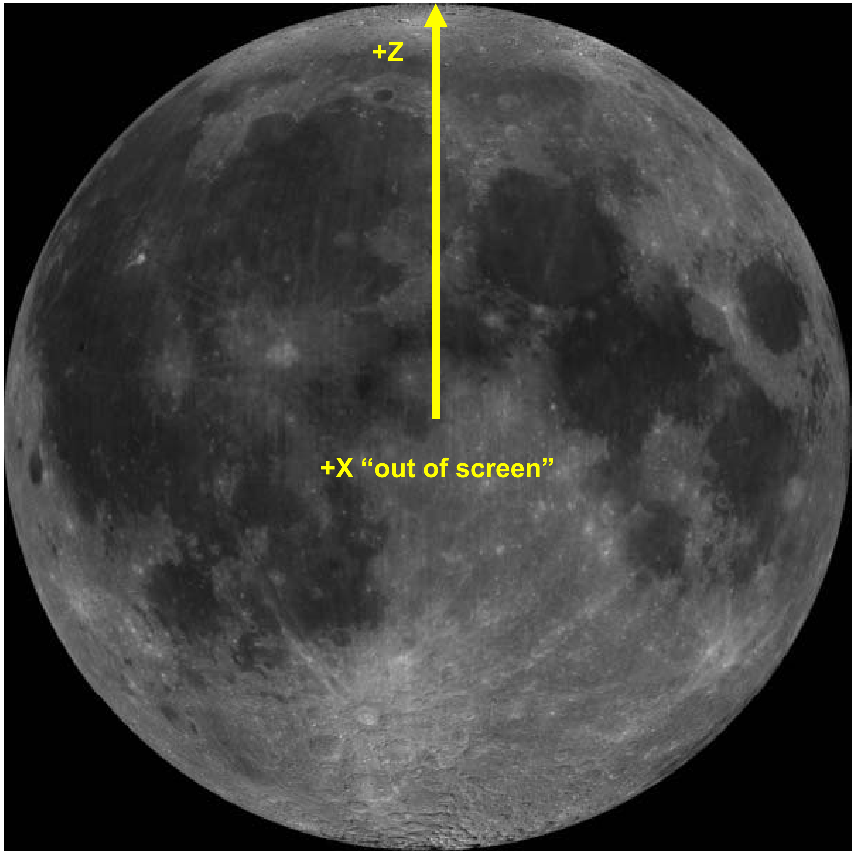
- Rotating coordinate system, fixed to moon
  - All lunar landmarks, including landing site vector, referenced to this system
- Origin at center of moon
- Axes:
  - +Z along true north pole



Moon as viewed from Earth

Moon-fixed Coordinate System

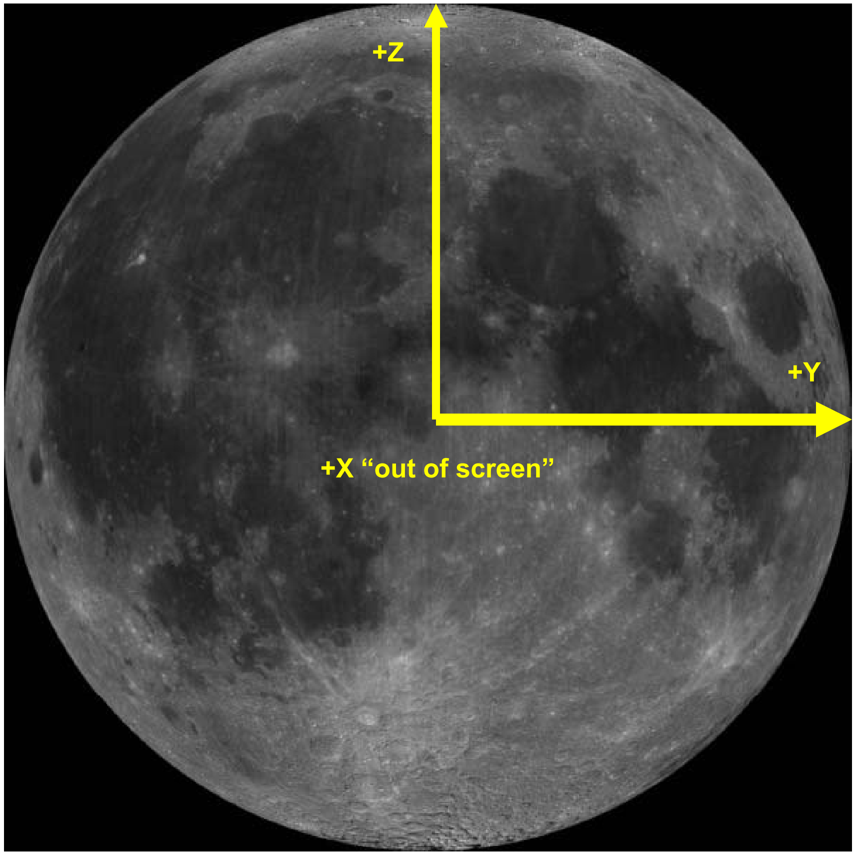
- Rotating coordinate system, fixed to moon
  – All lunar landmarks, including landing site vector, referenced to this system
- Origin at center of moon
- Axes:
  – +Z along true north pole
  – +X along zero longitude at equator (center of moon visible disc)



Moon as viewed from Earth

Moon-fixed Coordinate System

- Rotating coordinate system, fixed to moon
  – All lunar landmarks, including landing site vector, referenced to this system
- Origin at center of moon
- Axes:
  – +Z along true north pole
  – +X along zero longitude at equator (center of moon visible disc)
  – +Y completed right-handed system ("trailing" moon in its orbit around the Earth)



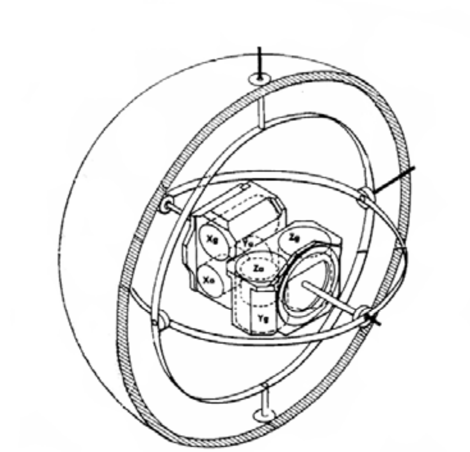
Moon as viewed from Earth

Objectives

- Review basic navigation concepts
- Describe coordinate systems
- **<u>Identify attitude determination techniques</u>**
  – **<u>Prime: PGNCS IMU Management</u>**
  – **<u>Backup: CSM SCS/LM AGS Attitude Management</u>**
- Identify state vector determination techniques
  – Prime: PGNCS Coasting Flight Navigation
  – Prime: PGNCS Powered Flight Navigation
  – Backup: LM AGS Navigation

PGNCS IMU Management

- Apollo used three-gimbal IMU
  - Lighter and less complex than four-gimbal IMU, but vulnerable to gimbal lock when all three gimbals in same plane
  - Spacecraft attitudes operationally constrained to avoid gimbal lock
- Apollo Flight Director Attitude Indicator (FDAI) driven directly by IMU gimbal angles rather than computer
  - Allowed IMU to operate independently of computer
  - Allowed gimbal lock region to be graphically depicted as red circles on FDAI ball
- Periodic IMU aligns to different REFSMMATs required to:
  - Accommodate variety of mission attitudes while avoiding gimbal lock
  - Provide meaningful FDAI attitude display to crew

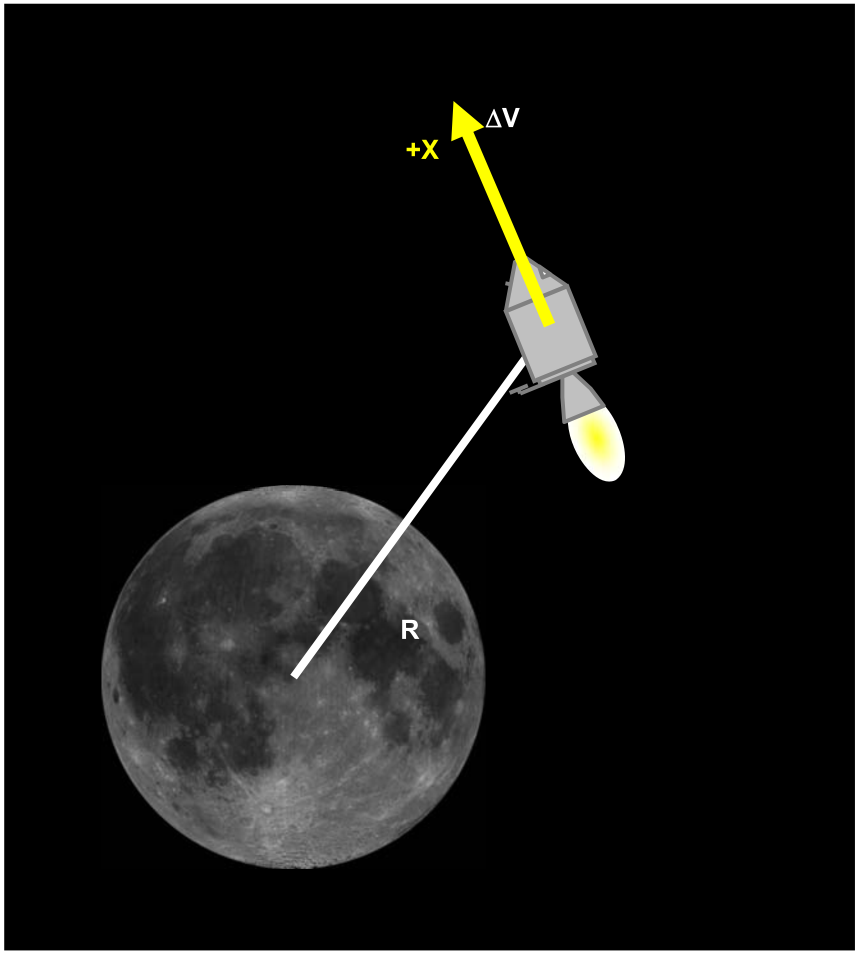


Common REFSMMATs

- Preferred
- Nominal (LVLH)
- Launch Pad (CSM only)
- Landing Site
- Liftoff
- Passive Thermal Control (PTC)
- Entry (CM only)

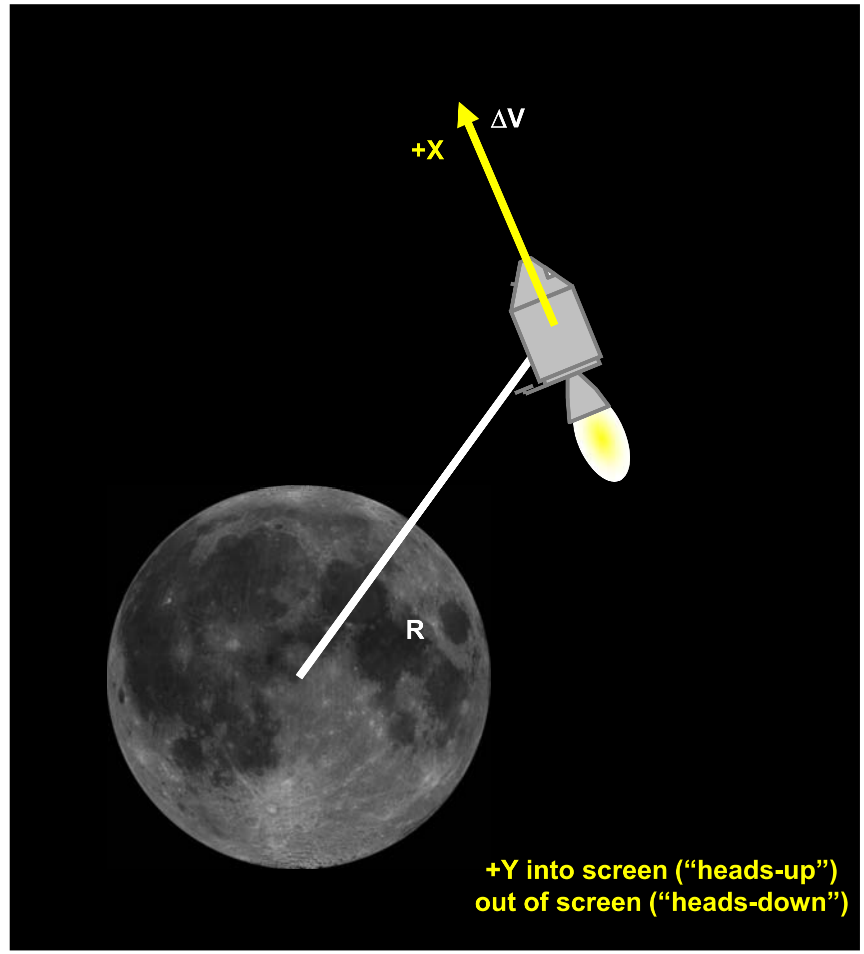
Preferred REFSMMAT

- Used for major burns
- +X aligned with ΔV vector at Time of Ignition (TIG)



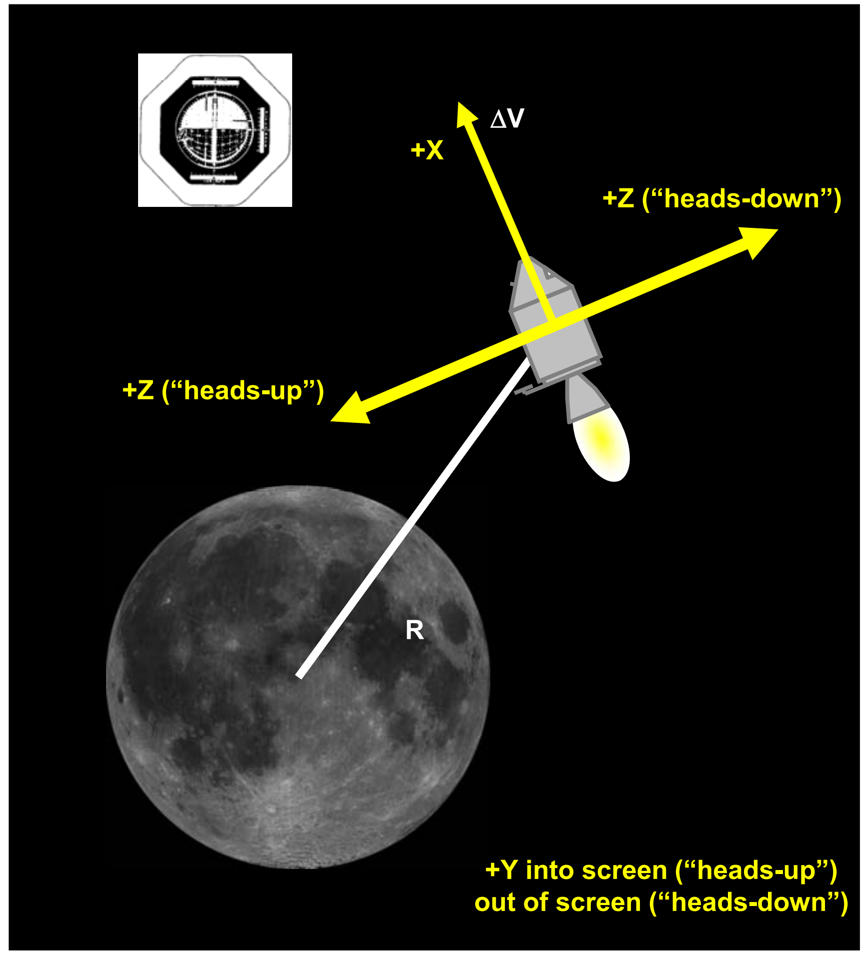
Preferred REFSMMAT

- Used for major burns
- +X aligned with ΔV vector at Time of Ignition (TIG)
- +Y perpendicular to both ΔV vector and position vector at TIG
  - Direction could be defined to provide either "heads-up" or "heads-down" burn attitude



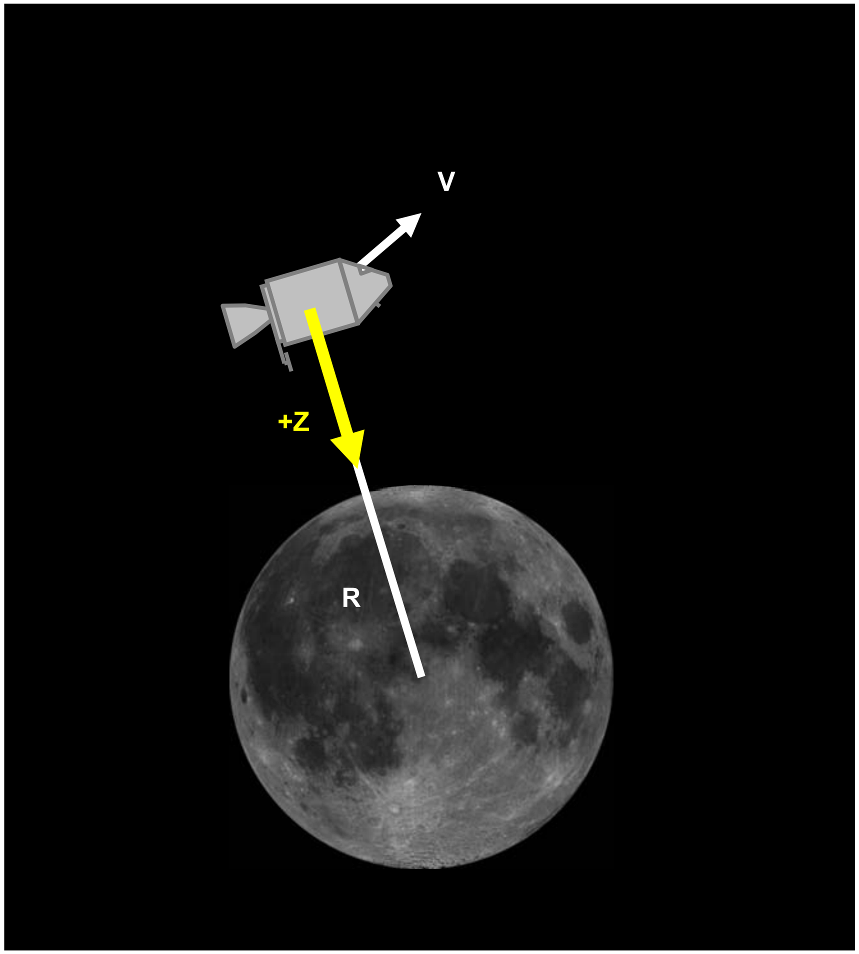
Preferred REFSMMAT

- Used for major burns
- +X aligned with ΔV vector at Time of Ignition (TIG)
- +Y perpendicular to both ΔV vector and position vector at TIG
  - Direction could be defined to provide either "heads-up" or "heads-down" burn attitude
- +Z completed right handed system
- FDAI read 0,0,0 when in burn attitude at TIG



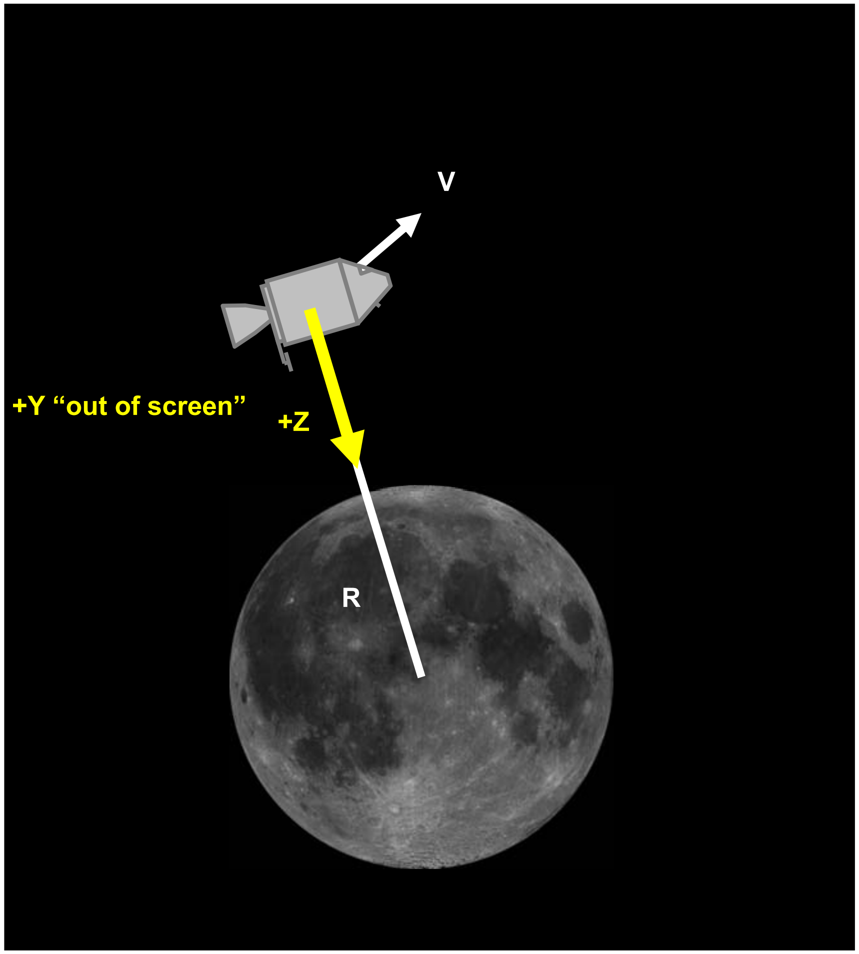
Nominal REFSMMAT

- Aligned with Local Vertical/Local Horizontal (LVLH) coordinates at time of alignment
- Used for coasting orbital flight
- +Z aligned with radius vector (+Rbar) at time of align



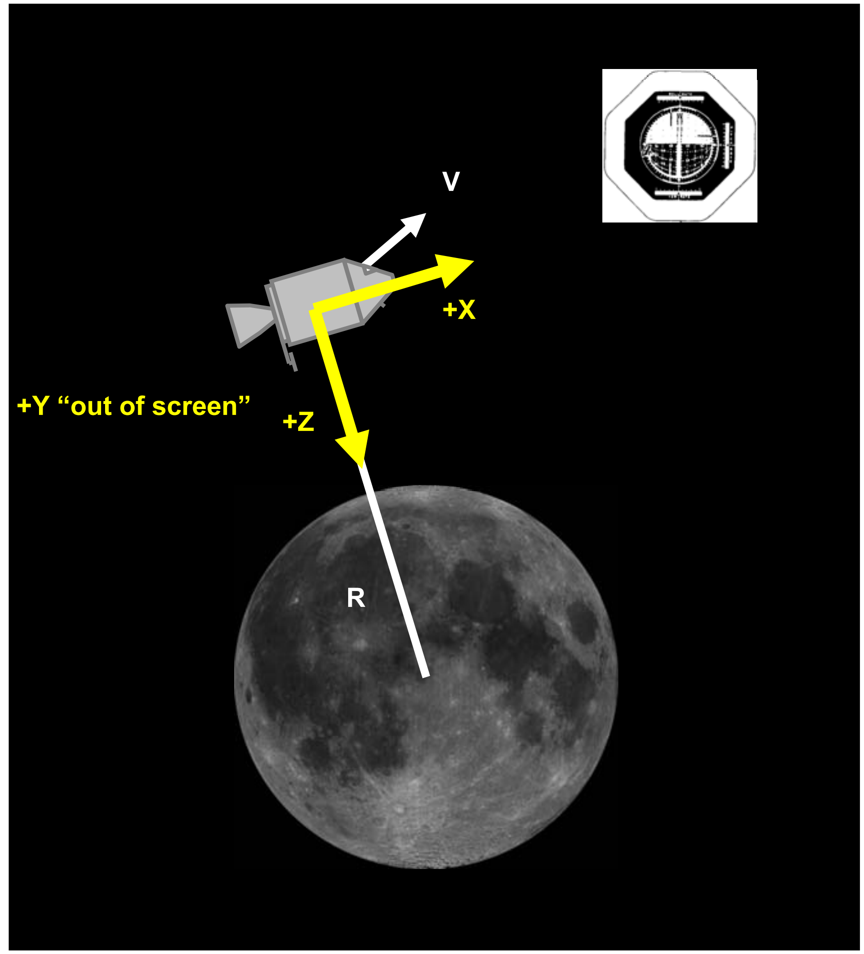
Nominal REFSMMAT

- Aligned with Local Vertical/Local Horizontal (LVLH) coordinates at time of alignment
- Used for coasting orbital flight
- +Z aligned with radius vector (+Rbar) at time of align
- +Y aligned with negative orbital momentum vector (-Hbar) at time of align



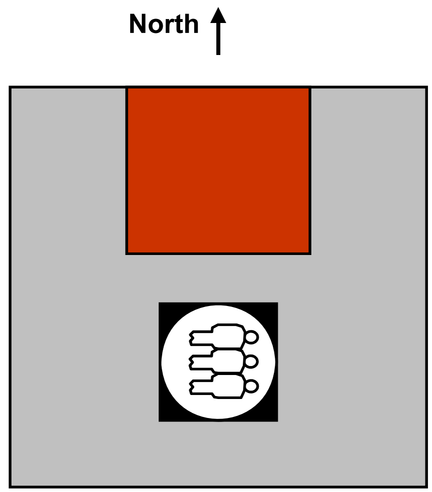
Nominal REFSMMAT

- Aligned with Local Vertical/Local Horizontal (LVLH) coordinates at time of alignment
- Used for coasting orbital flight
- +Z aligned with radius vector (+Rbar) at time of align
- +Y aligned with negative orbital momentum vector (-Hbar) at time of align
- +X in orbit plane in direction of velocity (+Vbar)
- FDAI read 0,0,0 when in “airplane attitude” **at time of align**
- Note that this was an inertial orientation aligned with LVLH only at one point in time
  - Inertial pitch angle diverged from LVLH pitch angle at orbital rate
  - Crew used Orbital Rate Display – Earth and Lunar (ORDEAL) to bias FDAI pitch angle to display LVLH attitude



Launch Pad REFSMMAT

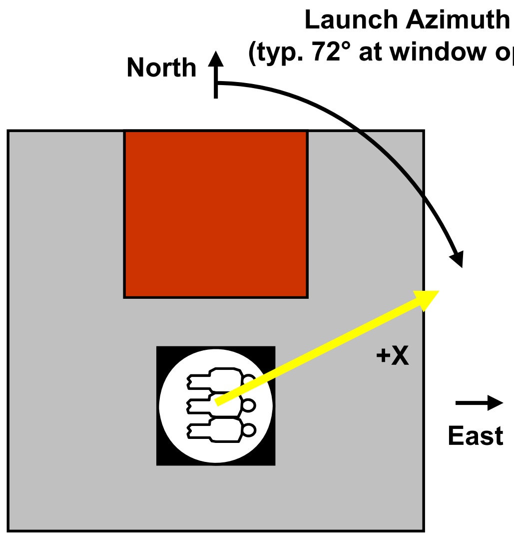
- CSM only
- +Z aligned with radius vector (+Rbar) at liftoff time



View of launch pad
from above

Launch Pad REFSMMAT

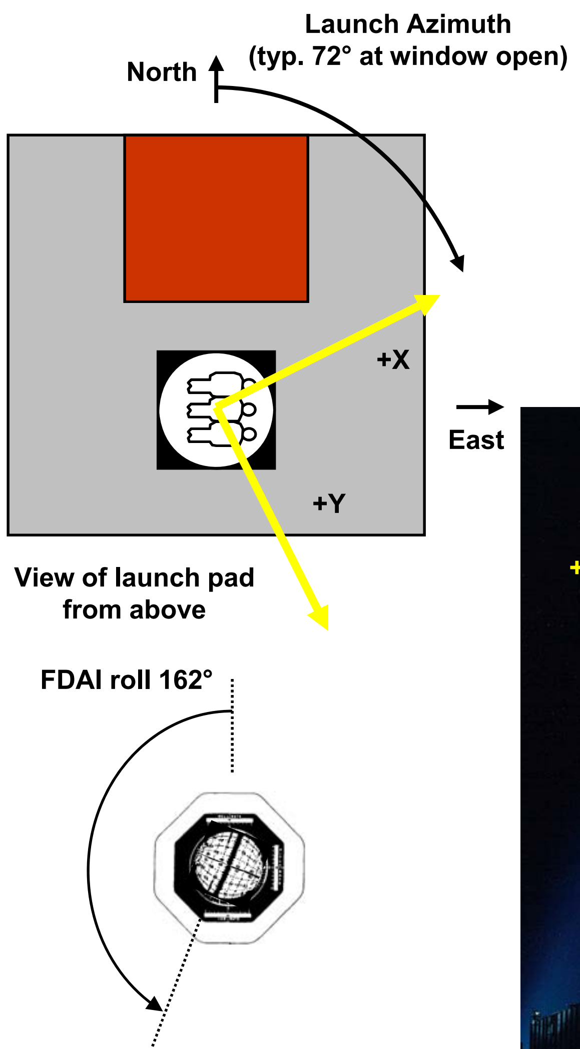
- CSM only
- +Z aligned with radius vector (+Rbar) at liftoff time
- +X aligned with flight azimuth at liftoff time



View of launch pad
from above

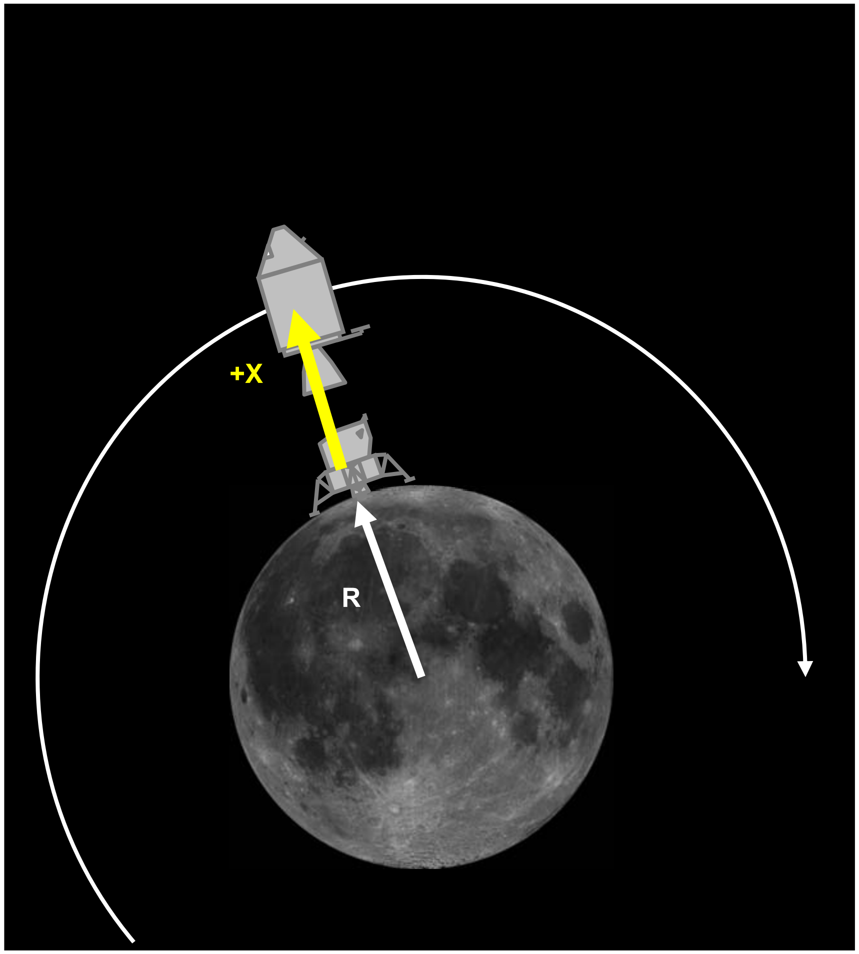
Launch Pad REFSMMAT

- CSM only
- +Z aligned with radius vector (+Rbar) at liftoff time
- +X aligned with flight azimuth at liftoff time
- +Y completed right-handed system
- At liftoff, FDAI read pitch 90, yaw 0, roll 90 plus flight azimuth



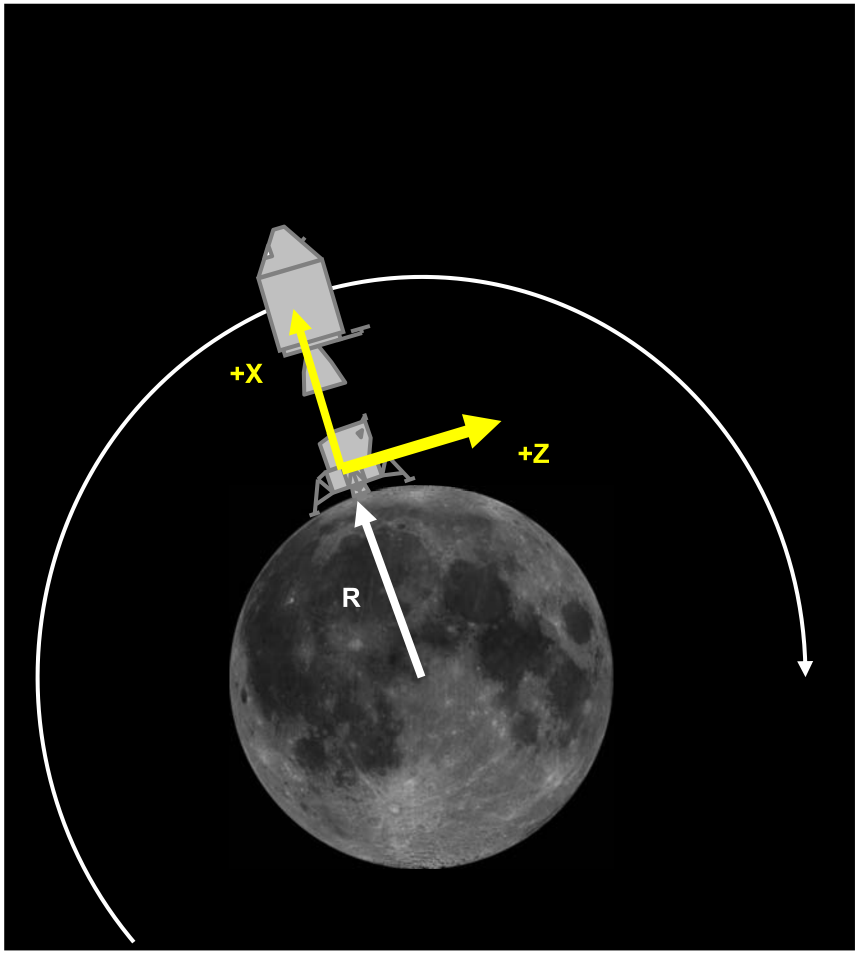
Landing Site and Liftoff REFSMMATs

- +X aligned with position vector at planned landing time



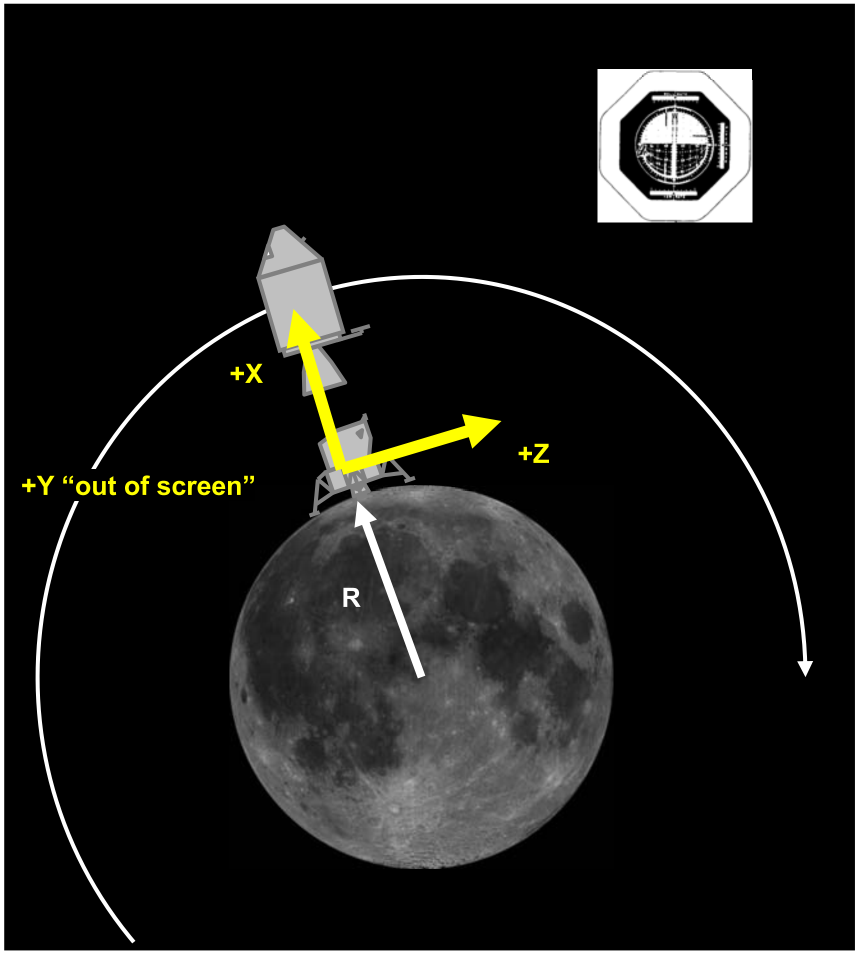
Landing Site and Liftoff REFSMMATs

- +X aligned with position vector at planned landing time
- +Z pointed "forward" (parallel to CSM orbit plane)



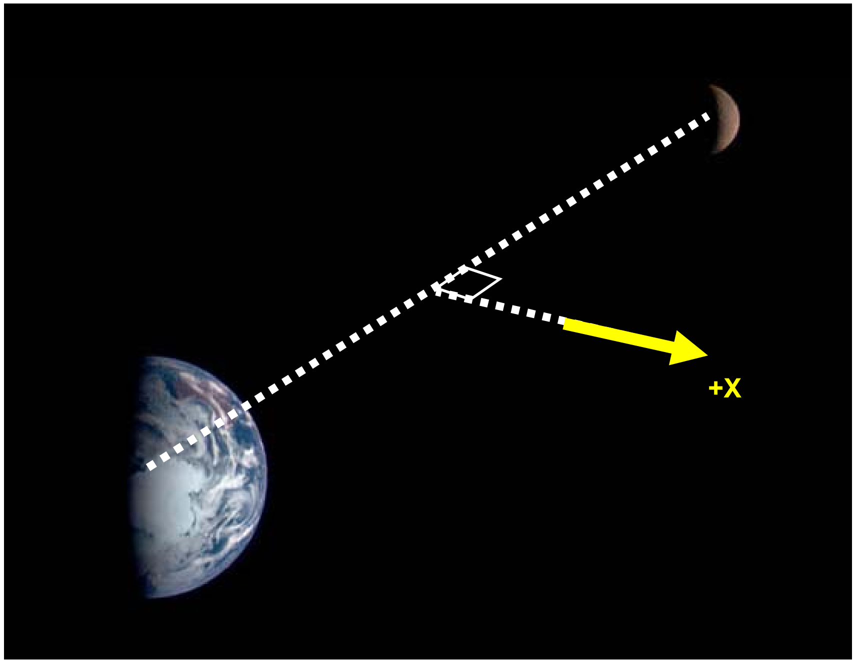
Landing Site and Liftoff REFSMMATs

- +X aligned with position vector at planned landing time
- +Z pointed "forward" (parallel to CSM orbit plane)
- +Y completed right-handed system
- LM FDAI read 0,0,0 at landing
- Liftoff REFSMMAT identical except defined at planned lunar liftoff time



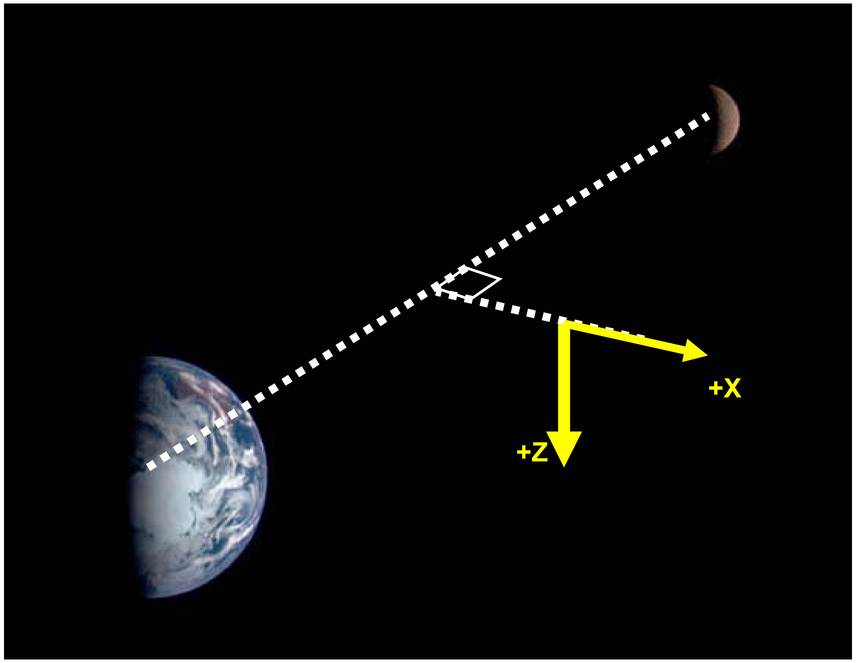
PTC REFSMMAT

- Used for passive thermal control ("barbecue roll") during translunar/transearth coast
- +X in ecliptic plane perpendicular to Earth-moon line



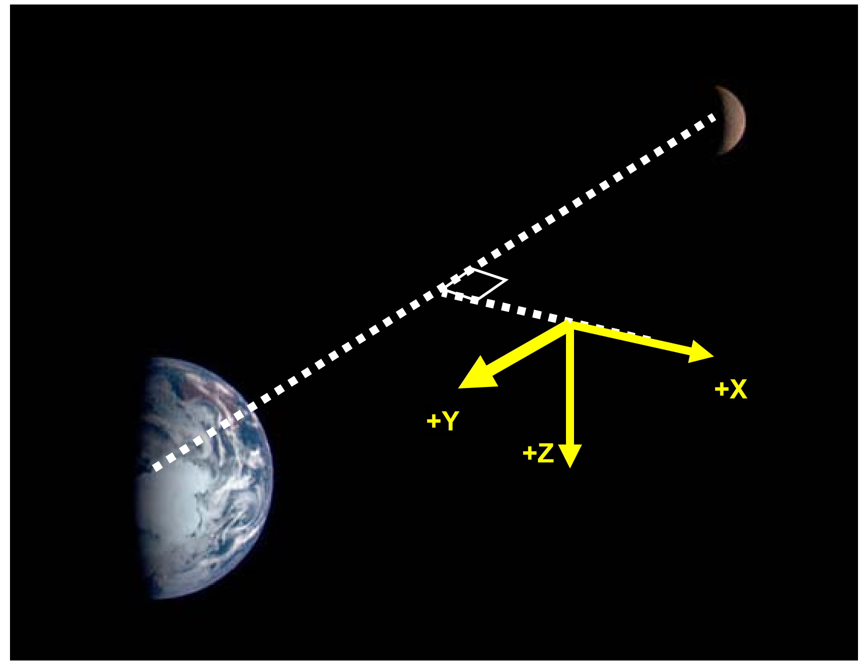
PTC REFSMMAT

- Used for passive thermal control (“barbecue roll”) during translunar/transearth coast
- +X in ecliptic plane perpendicular to Earth-moon line
- +Z perpendicular to ecliptic plane directed south



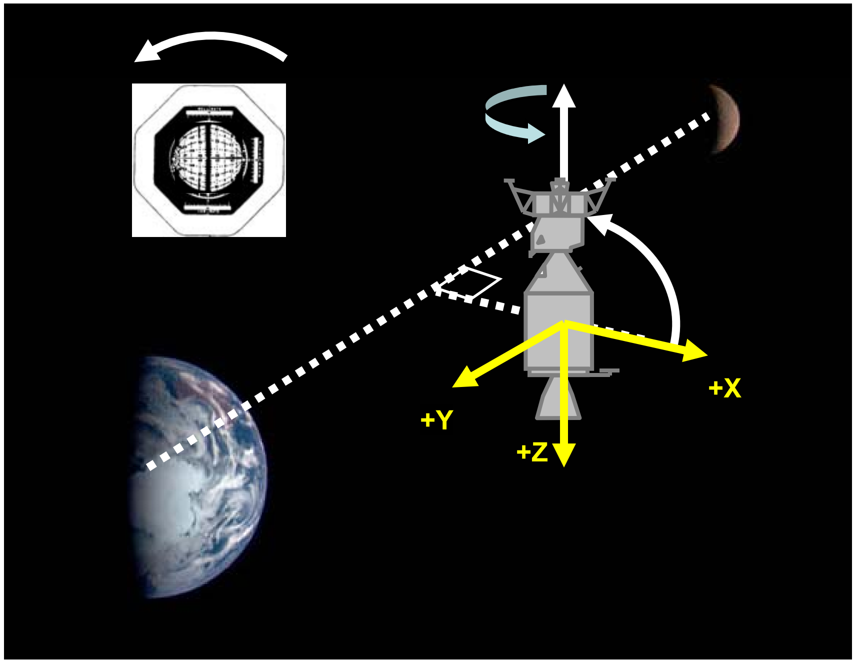
PTC REFSMMAT

- Used for passive thermal control ("barbecue roll") during translunar/transearth coast
- +X in ecliptic plane perpendicular to Earth-moon line
- +Z perpendicular to ecliptic plane directed south
- +Y completed right-handed system



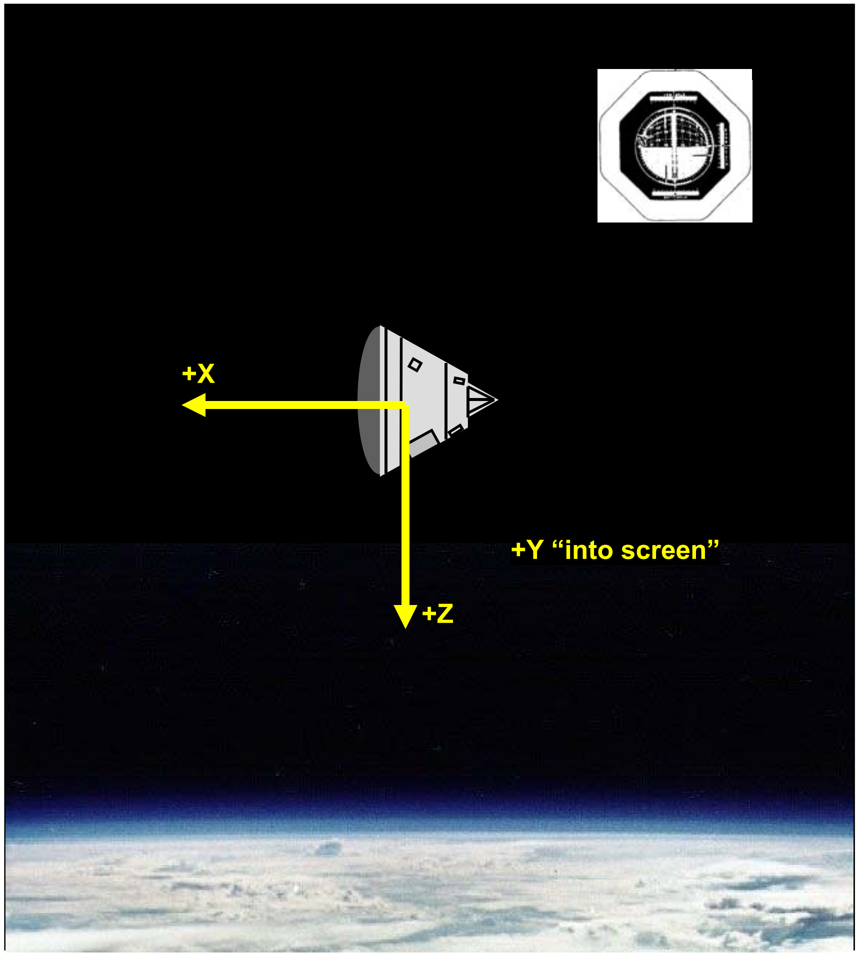
PTC REFSMMAT

- Used for passive thermal control (“barbecue roll”) during translunar/transearth coast
- +X in ecliptic plane perpendicular to Earth-moon line
- +Z perpendicular to ecliptic plane directed south
- +Y completed right-handed system
- PTC roll initiated from 90 deg pitch attitude to place CSM/LM stack perpendicular to ecliptic (and hence, line of sight to sun)



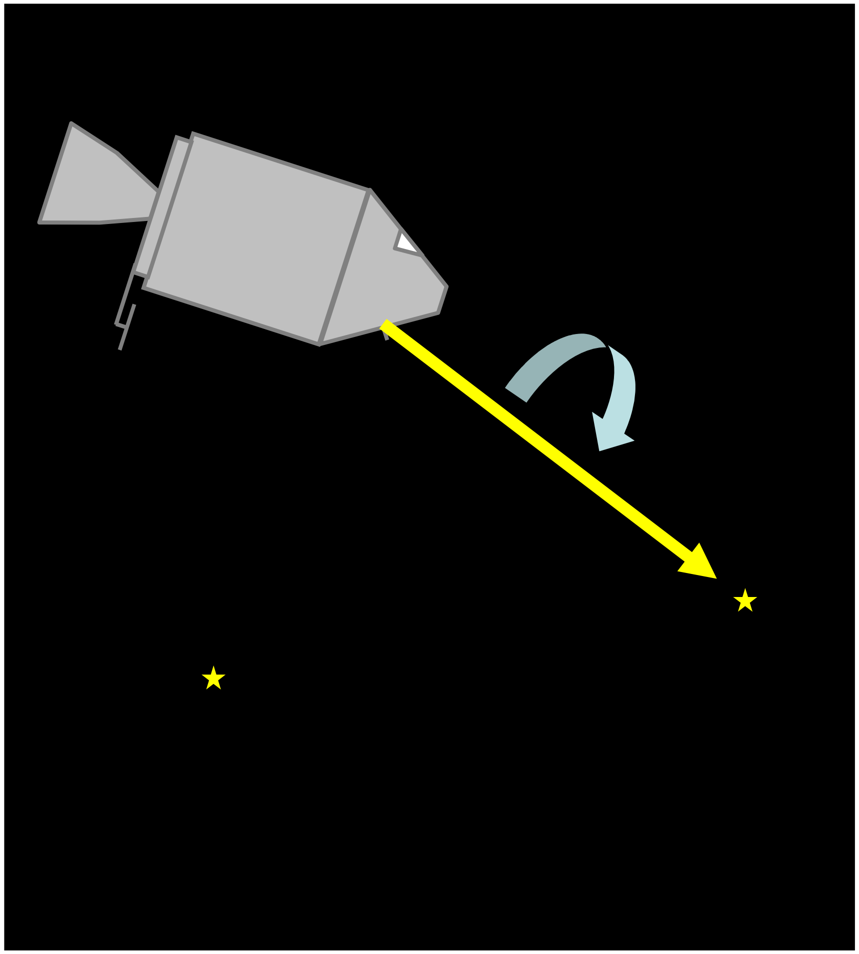
Entry REFSMMAT

- Aligned with LVLH at predicted time of Entry Interface (EI), 122 km (400 kft) altitude
- FDAI read pitch 180, 0, 0 in heads-down heat-shield forward attitude at EI
- Note that nominal EI attitude pitched 20 degrees above local horizontal



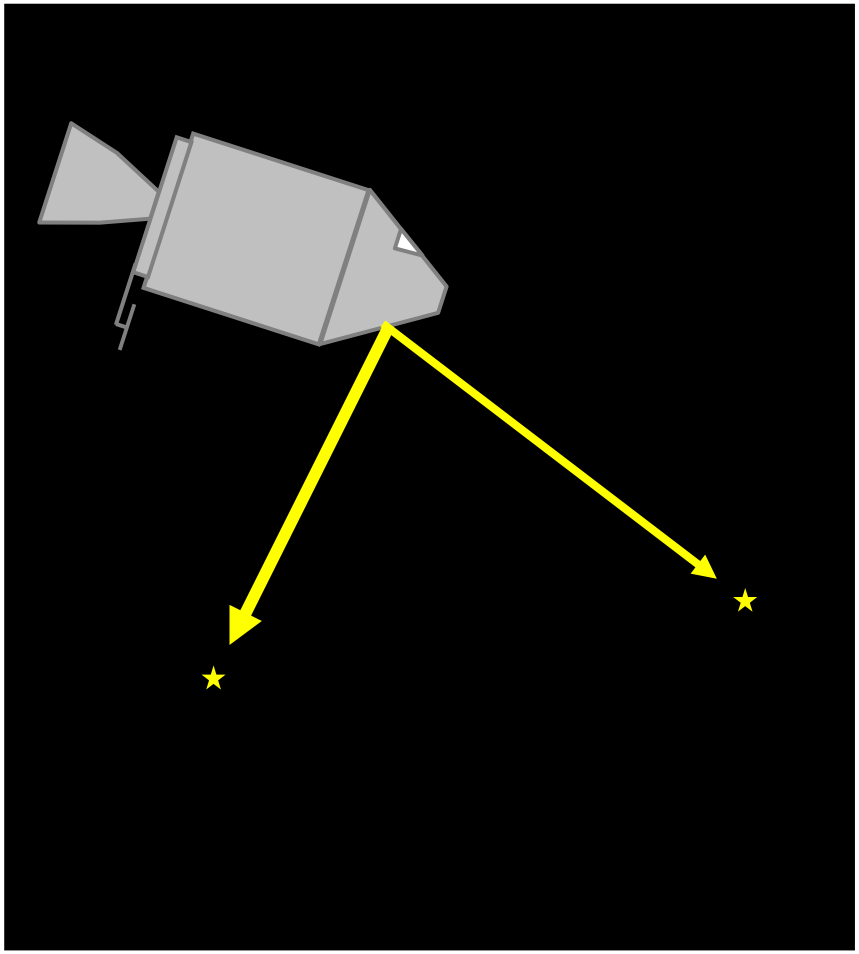
IMU Alignment Techniques

- Two vectors required to uniquely define orientation of one frame with respect to another
  - First vector fixes a line of sight (LOS) but leaves one degree of freedom (rotation about LOS)



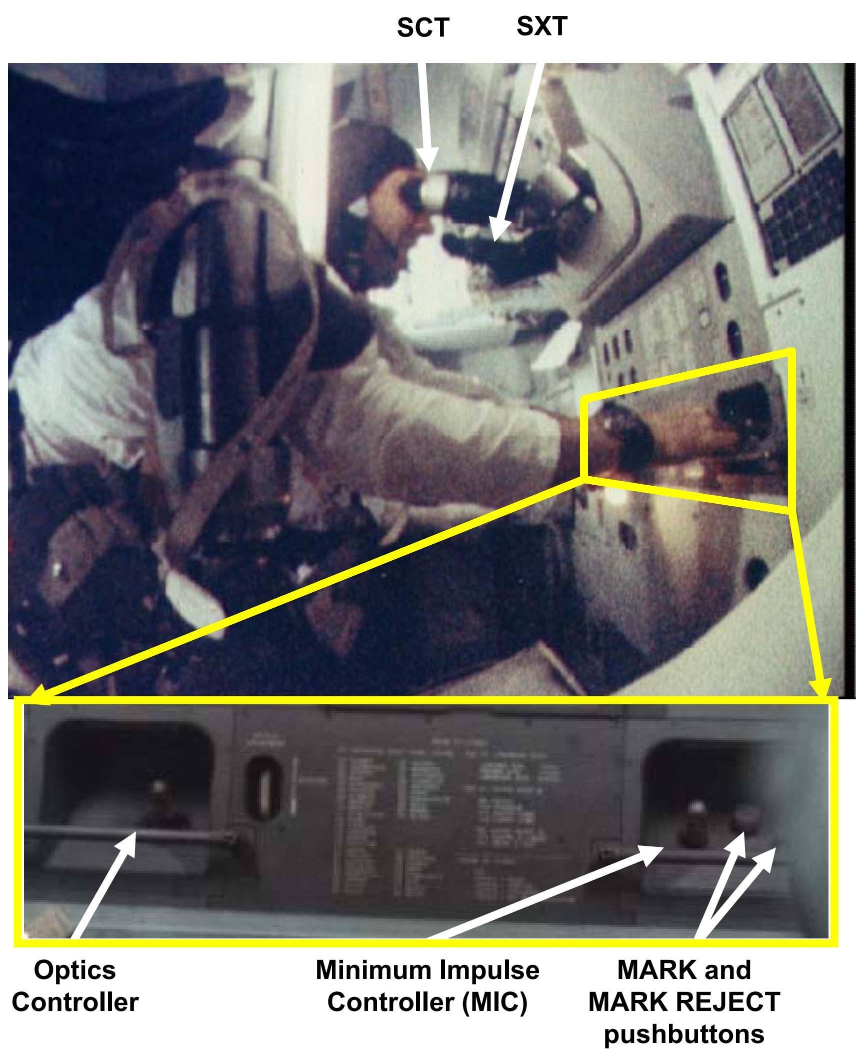
IMU Alignment Techniques

- Two vectors required to uniquely define orientation of one frame with respect to another
  - First vector fixes a line of sight (LOS) but leaves one degree of freedom (rotation about LOS)
  - Second vector fixes rotation about LOS



CSM IMU Alignment

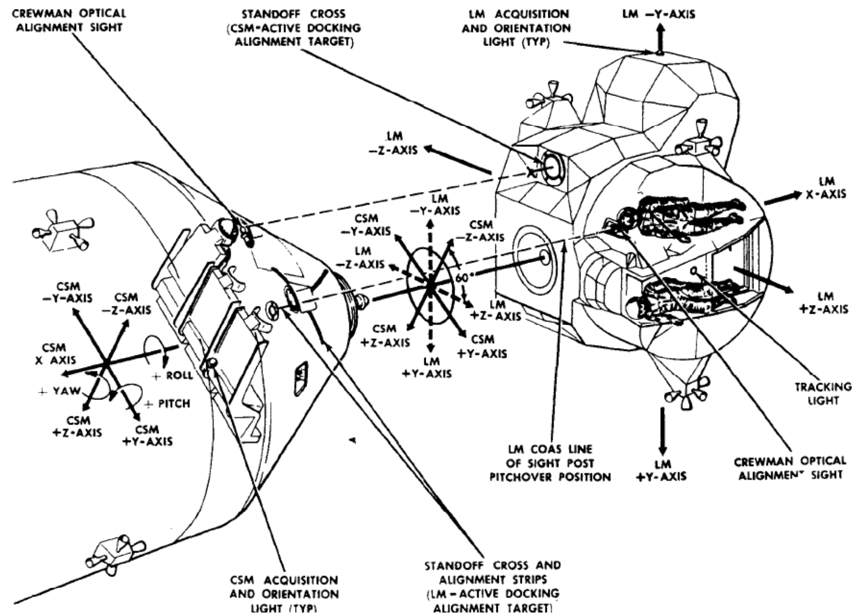
- Crew marked on two stars (or other known celestial bodies) using the sextant (SXT) or scanning telescope (SCT)
- Auto optics modes allowed SXT/SCT shaft and trunnion to be pointed directly at stars selected by the computer
- Manual optics modes allowed tweaking of SXT/SCT shaft/trunnion using optics controller
- Minimum Impulse Controller (MIC) could be used to tweak CSM attitude
- Crewman Optical Alignment Sight (COAS) could be used as backup alignment device if optics failed
  - Not attached to navigation base – calibration required prior to use



LM Docked IMU Alignment

- Initial coarse alignment used CM gimbal angles
- Docking mechanism did not tightly constrain relative roll
  – Crew recorded docking angle (R_c) from index marks on tunnel during initial LM activation
- Required LM gimbal angles computed manually from CM gimbal angles as follows:

$$OGA_{LM} = 300° + R_c - OGA_{CM}$$
$$IGA_{LM} = 180° + IGA_{CM}$$
$$MGA_{LM} = 360° - MGA_{CM}$$



DOCKED IMU COARSE ALIGN

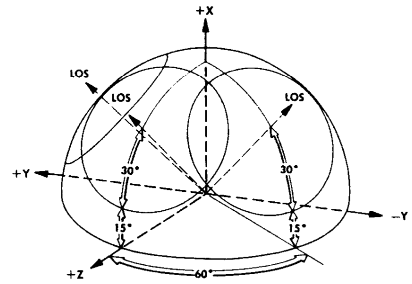
1 Verify CSM In Min DEADBAND ATT HOLD 1

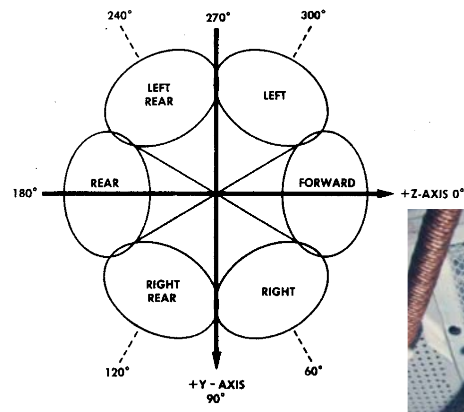
2 Calculate LM Gimbal Angles

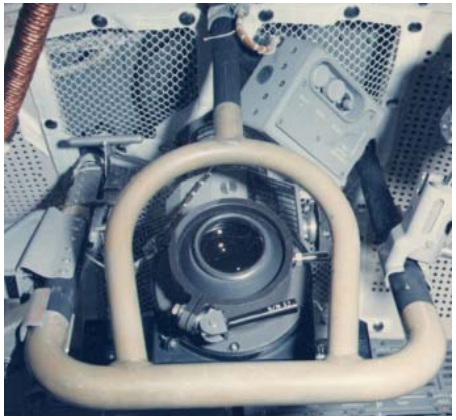
OG		IG		MG		
300.00		180.00		360.00		2
___ . ___	+Rc (See 1-1)					3
___ . ___ (7.5)	-CM	___ . ___ (112.5)	+CM	___ . ___ (22.5)	-CM	
___ . ___ (292.5)	LM	___ . ___ (292.5)	LM	___ . ___ (337.5)	LM	

LM Orbital IMU Alignment

- Crew marked on two stars (or other known celestial bodies) using the alignment optical telescope (AOT)
- AOT had six detent positions; however, only forward position could be used while docked to CSM
- Rendezvous Radar (RR) antenna required to be positioned out of AOT field-of-view
- Crew entered detent position code and star code manually into computer
- COAS could be used as backup (same calibration restrictions as CSM)

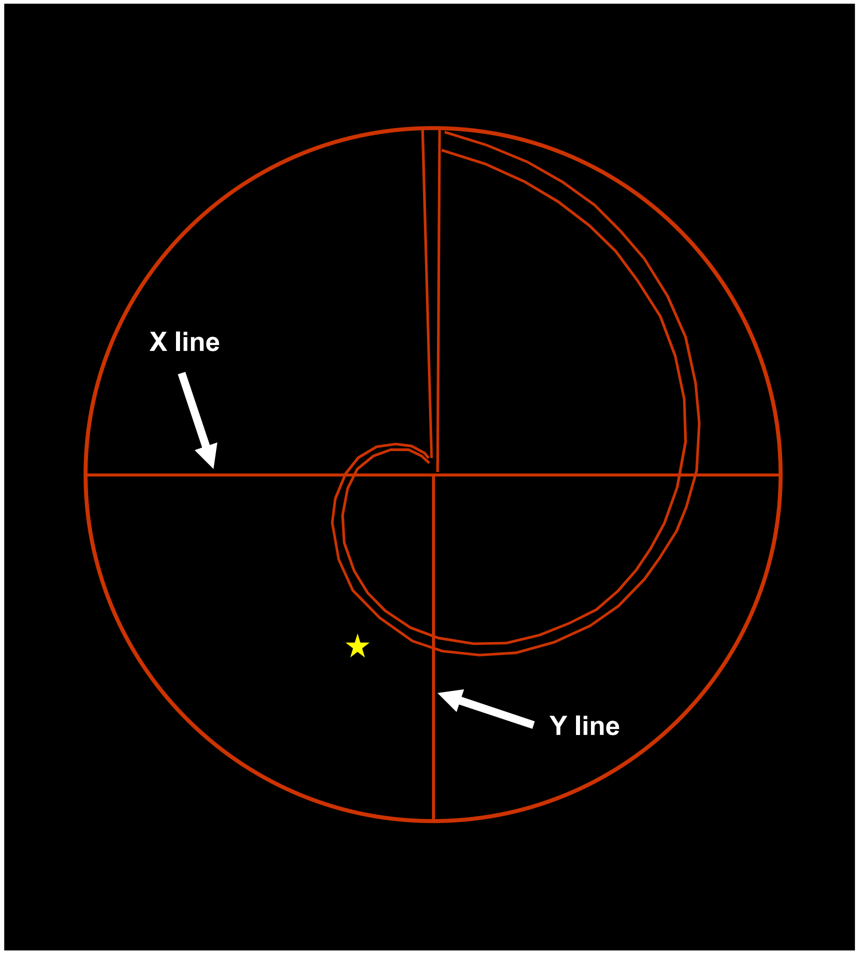






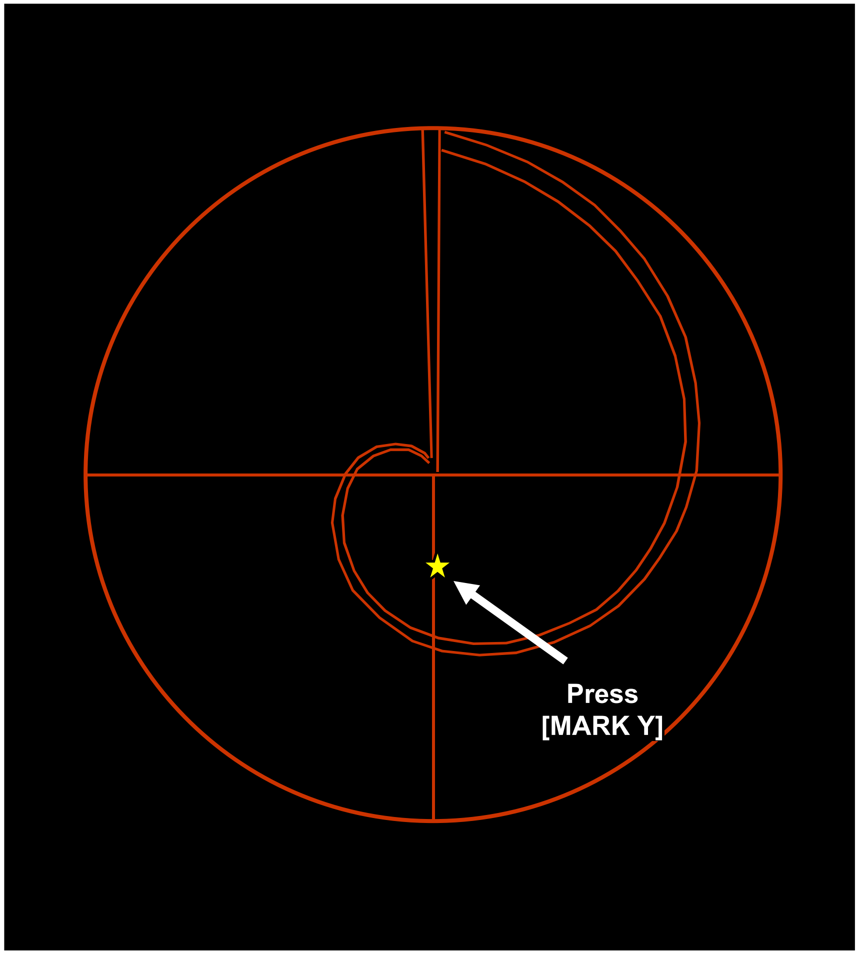
LM AOT Usage

- X-line and Y-line on AOT reticle used for in-flight alignment
- Crew allowed star to drift across AOT field-of-view



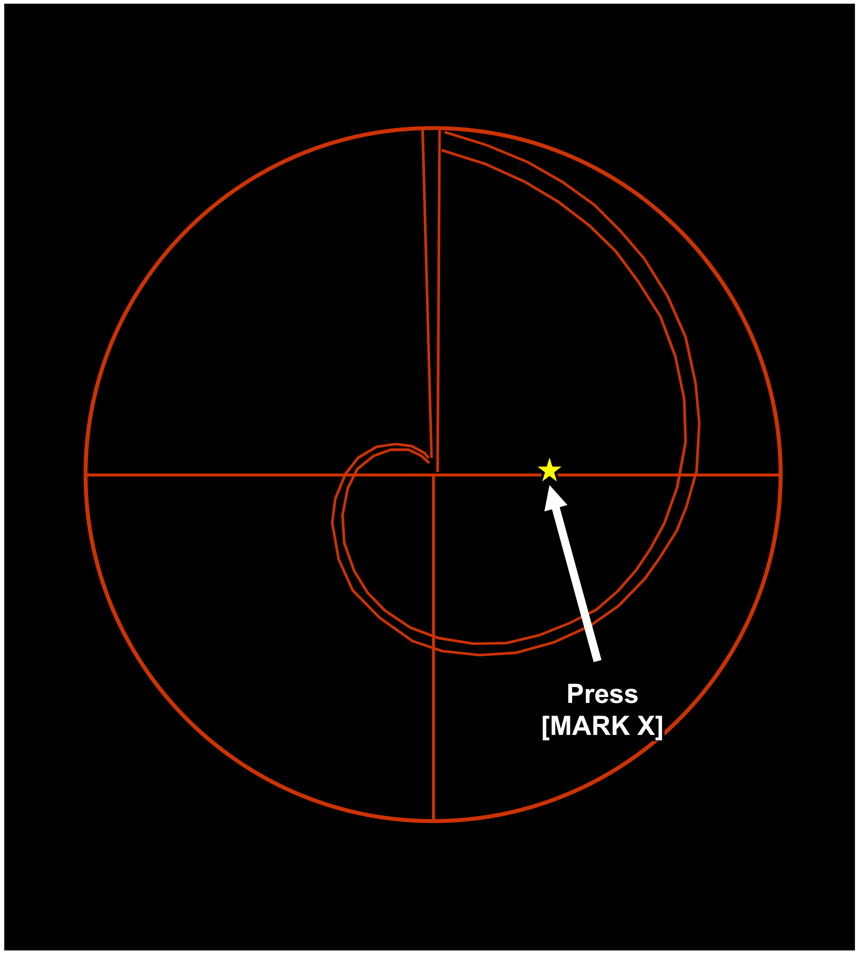
LM AOT Usage

- X-line and Y-line on AOT reticle used for in-flight alignment
- Crew allowed star to drift across AOT field-of-view
- Crew pressed [MARK Y] when star crossed Y-line



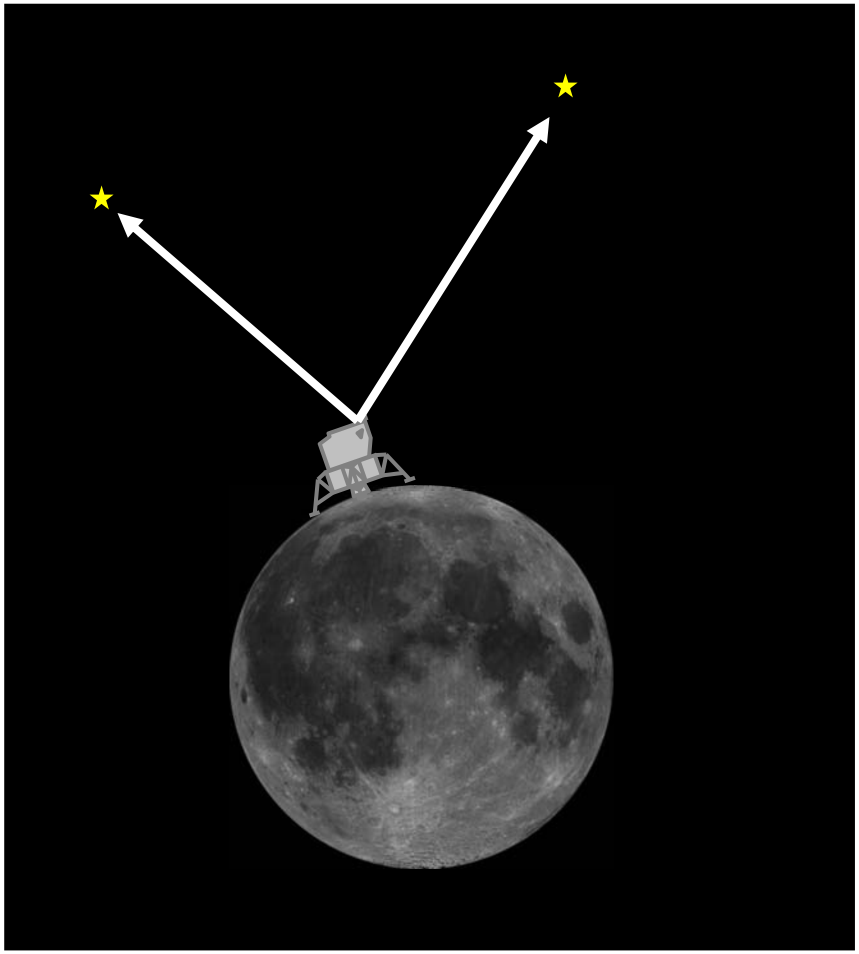
LM AOT Usage

- X-line and Y-line on AOT reticle used for in-flight alignment
- Crew allowed star to drift across AOT field-of-view
- Crew pressed [MARK Y] when star crossed Y-line
- Crew pressed [MARK X] when star crossed X-line
- Marks could be taken in either order
- Crew pressed [MARK REJECT] if bad mark



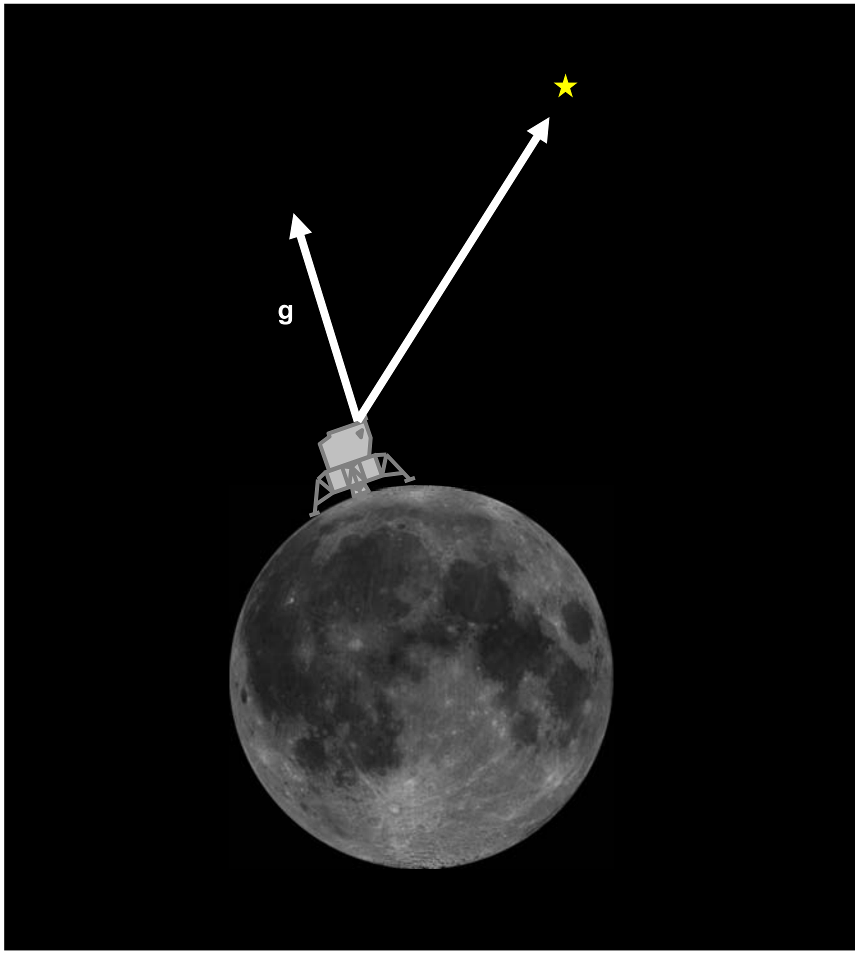
LM Lunar Surface IMU Alignment

- Not always possible to sight on two stars while on surface



LM Lunar Surface IMU Alignment

- Not always possible to sight on two stars while on surface
- For first surface alignment, local gravity vector (as measured by IMU accelerometers) could be substituted for one of the star sightings

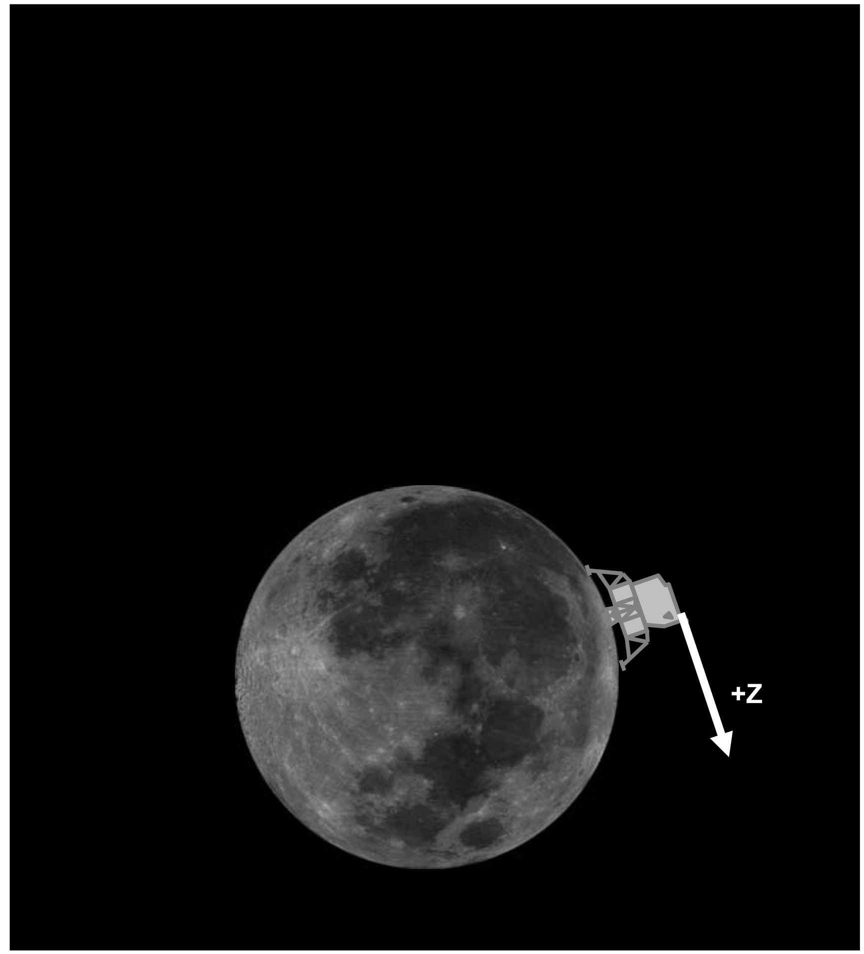


LM Lunar Surface IMU Alignment

- Not always possible to sight on two stars while on surface
- For first surface alignment, local gravity vector (as measured by IMU accelerometers) could be substituted for one of the star sightings
- Present orientation of LM Y and Z axes stored in moon-fixed coordinates at conclusion of each alignment

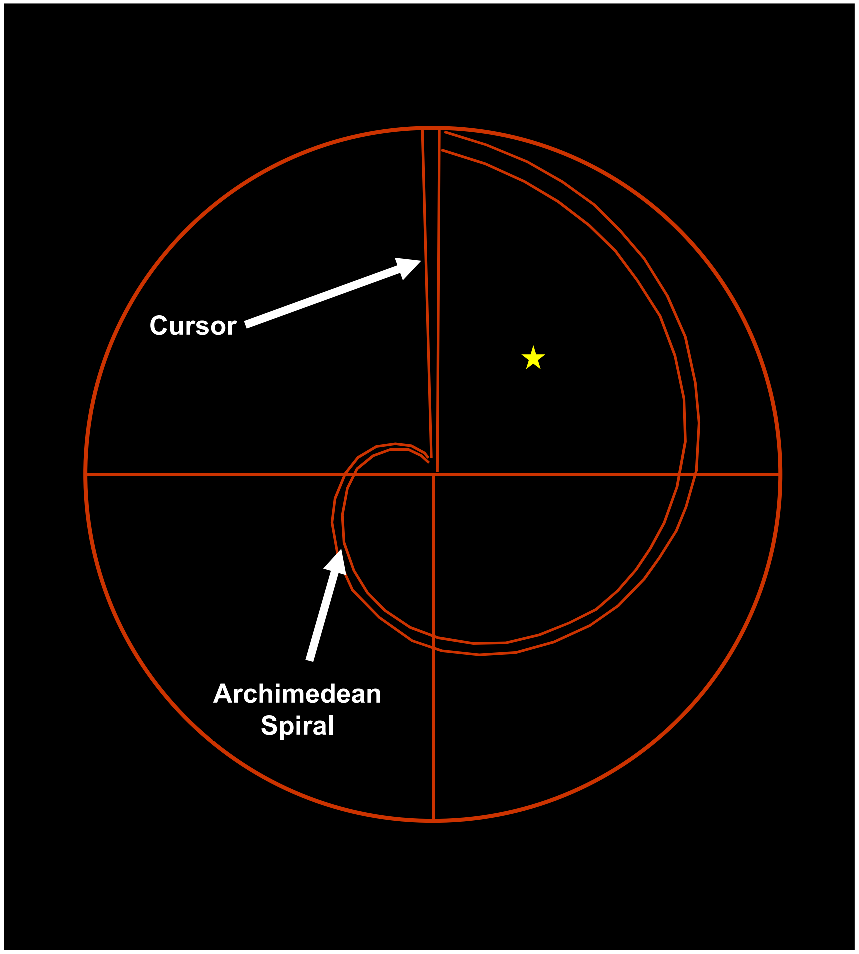
LM Lunar Surface IMU Alignment

- Not always possible to sight on two stars while on surface
- For first surface alignment, local gravity vector (as measured by IMU accelerometers) could be substituted for one of the star sightings
- Present orientation of LM Y and Z axes stored in moon-fixed coordinates at conclusion of each alignment
- For second and subsequent alignments, could use either gravity vector and present Z axis, or present Y and Z axes



LM AOT Surface Usage

- Stars may never cross AOT X or Y lines while on surface
  - LM in fixed attitude
  - Moon rotates very slowly
  - Different marking technique required
- AOT reticle had two additional markings
  - Radial “cursor”
  - Archimedean “spiral” (radius increases linearly with angle)
- AOT reticle rotated to allow cursor or spiral to be superimposed on star
  - Reticle angle displayed on counter, manually entered via DSKY



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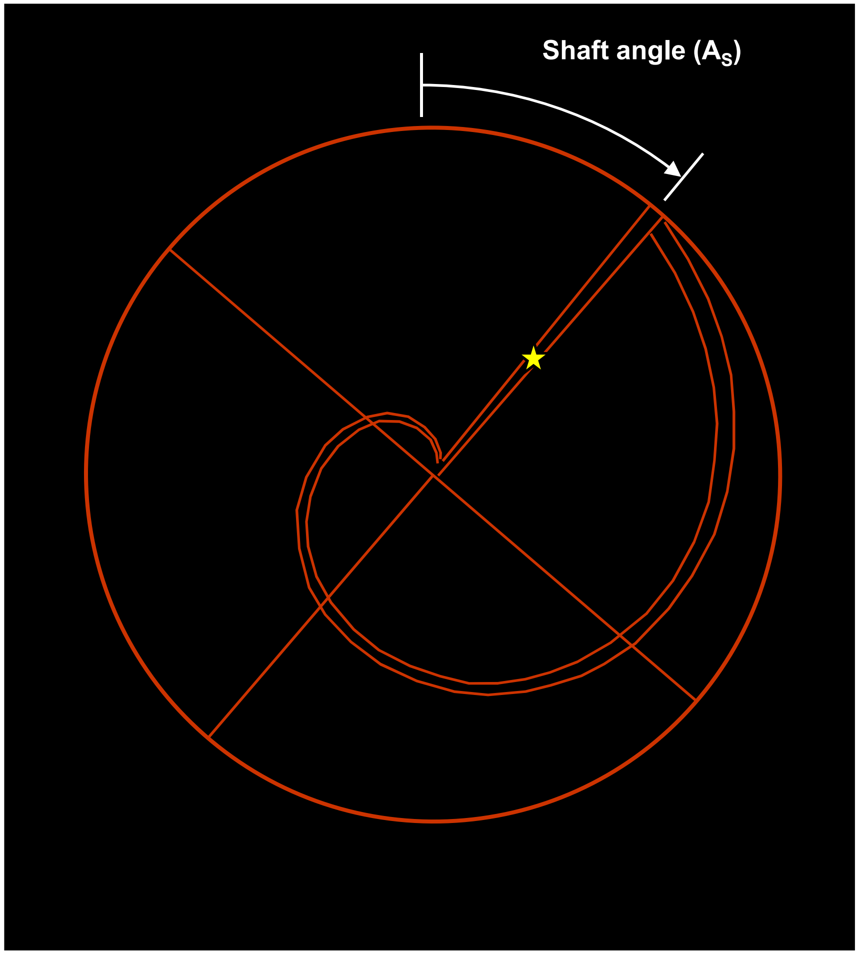

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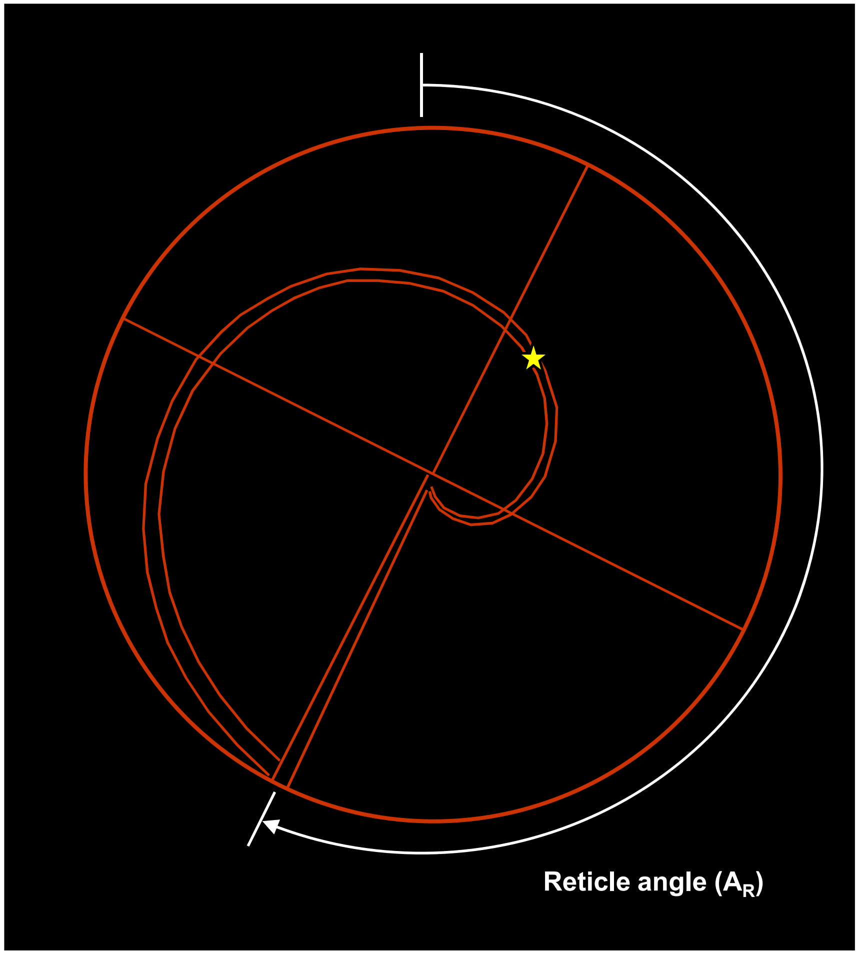
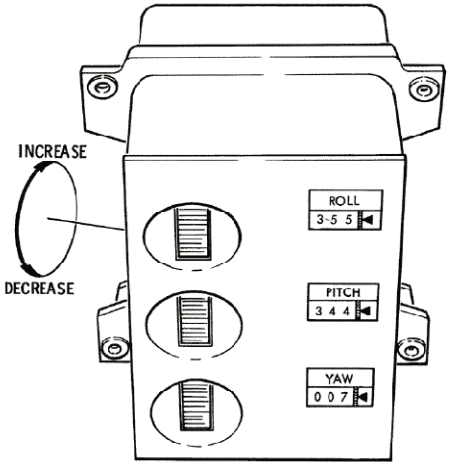


CSM SCS Attitude Management

- Stabilization and Control System (SCS) served as backup control system for the Primary Guidance, Navigation, and Control System (PGNCS)
- Attitude reference provided by two Gyro Assemblies (GAs), each of which contained three Body Mounted Attitude Gyros (BMAGs)
- GA2 BMAGs measure attitude rate
- GA1 BMAGs nominally measure attitude change from reference attitude but could be configured to measure rates as backup to GA2

CSM SCS Attitude Management

- Gyro Display Coupler (GDC) combined GA1 attitude difference with reference attitude to produce total attitude for display to crew
- Reference attitude set to current IMU attitude on Attitude Set Control Panel (ASCP), then GDC aligned to reference
- BMAGs were more “drifty” than IMU



LM AGS Attitude Management

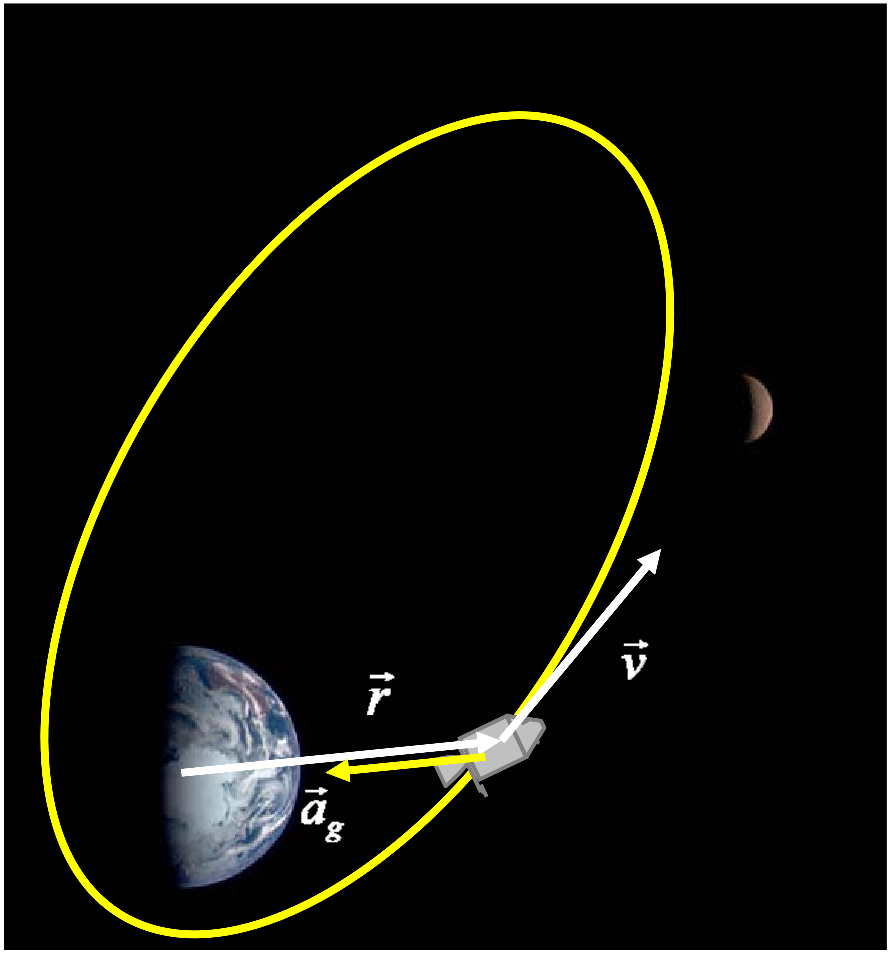
- Abort Sensor Assembly (ASA) was strapdown inertial navigation system for the Abort Guidance System (AGS)
- AGS had access to PGNS downlist data via telemetry link
- Crew had capability to command AGS to align ASA to IMU
- AGS could also calibrate ASA gyro/accelerometer biases using IMU as reference

Objectives

- Review basic navigation concepts
- Describe coordinate systems
- Identify attitude determination techniques
  - Prime: PGNCS IMU Management
  - Backup: CSM SCS/LM AGS Attitude Management
- **Identify state vector determination techniques**
  - **Prime: PGNCS Coasting Flight Navigation**
  - **Prime: PGNCS Powered Flight Navigation**
  - **Backup: LM AGS Navigation**

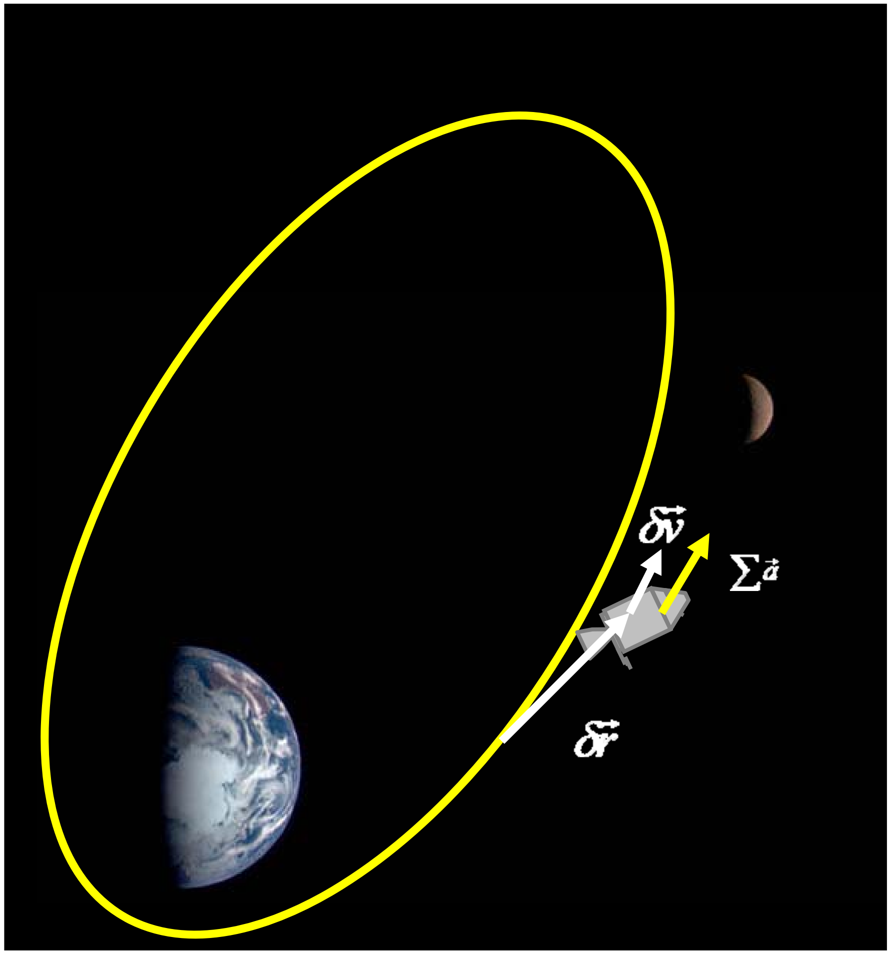
Coasting Integration

- Encke's Method
  - Use current state vector and gravity of primary body to compute a reference conic



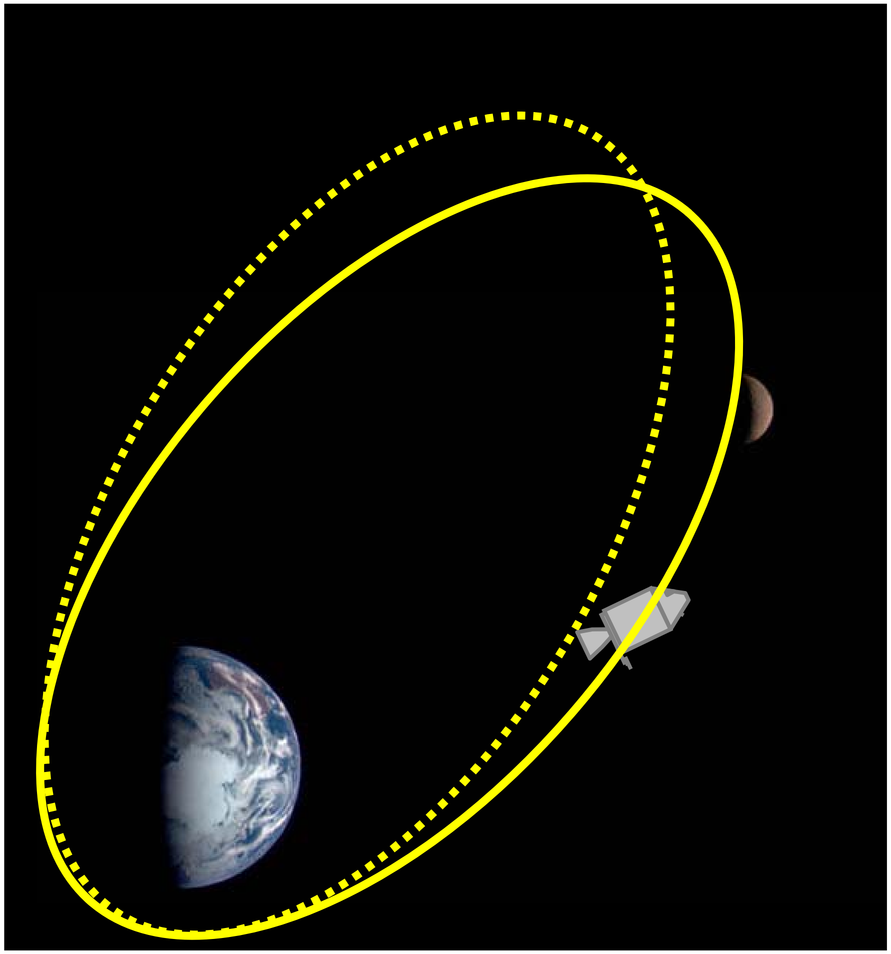
Coasting Integration

- Encke's Method
  - Use current state vector and gravity of primary body to compute a reference conic
  - Sum all other accelerations to propagate a position/velocity deviance from the reference conic



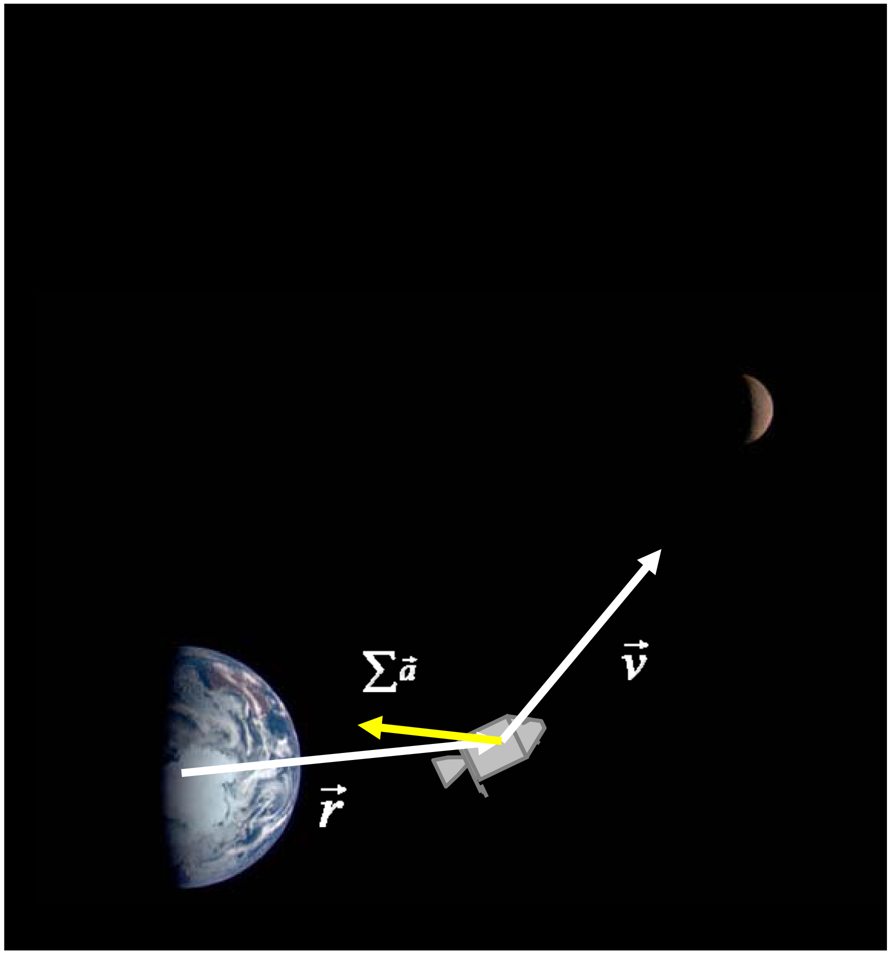
Coasting Integration

- Encke's Method
  - Use current state vector and gravity of primary body to compute a reference conic
  - Sum all other accelerations to propagate a position/velocity deviance from the reference conic
  - When deviances exceed threshold, compute new reference conic and zero the deviations (rectification)



Coasting Integration

- Compare to Cowell's Method (shuttle):
  - Sum all accelerations on vehicle (including primary body gravity) and propagate directly to advance the state vector
- Cowell's advantage: simpler, brute-force algorithm
- Encke's advantages:
  - Maintains more precision at larger stepsizes
  - More suitable for slow computers with limited precision (i.e. Apollo Guidance Computer)



Perturbing Accelerations

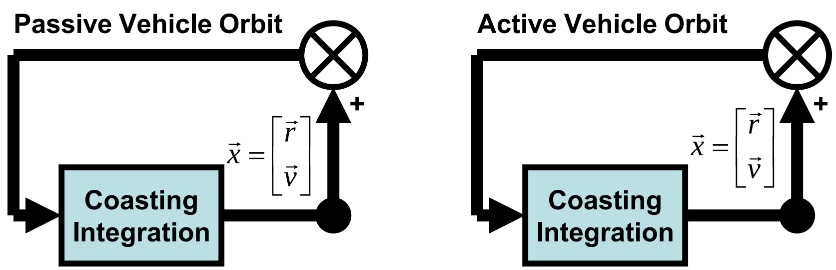
- Depended on phase of mission
- Earth or lunar orbit: non-spherical gravity of primary body (up to fourth order terms)
- Translunar/transearth coast: Earth, lunar, and solar gravity (spherical terms only)
- No drag
- No IMU acceleration

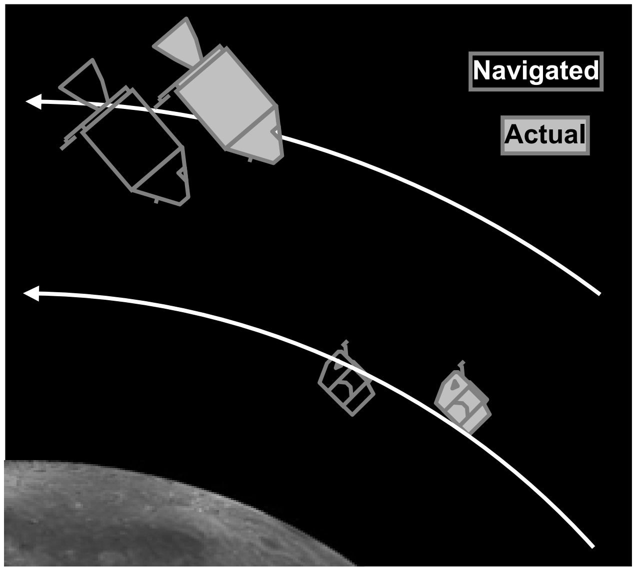
Measurement Incorporation

- Several different programs available, not all on both vehicles
- MCC prime for most forms of navigation; onboard capability intended as loss-of-comm backup

Program	CSM	LM	Prime
Rendezvous	√	√	Onboard
Orbital	√		MCC
Cislunar-midcourse	√		MCC
Lunar Surface		√	MCC

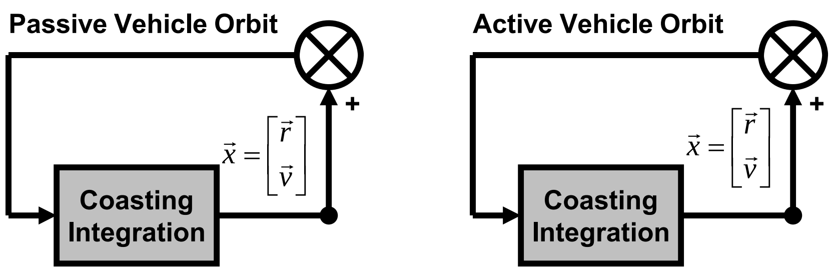
LM Rendezvous Navigation

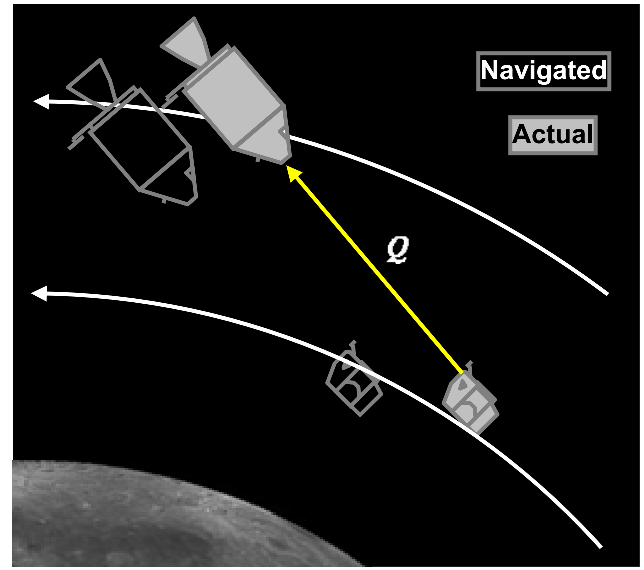




- The state vectors for both vehicles are propagated to the current time

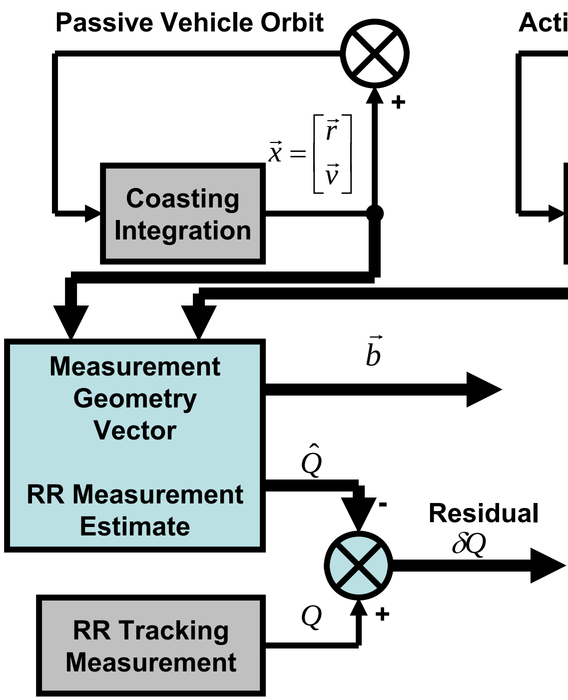
LM Rendezvous Navigation

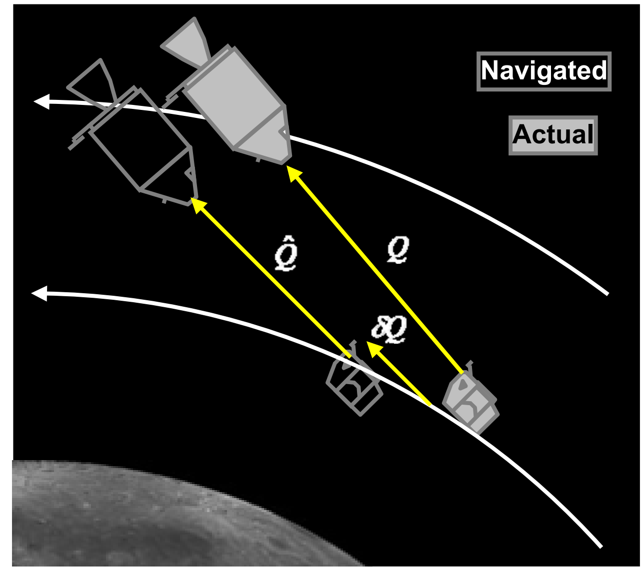




- The LM RR takes a measurement (range, range rate, shaft, or trunnion angle) of the CSM

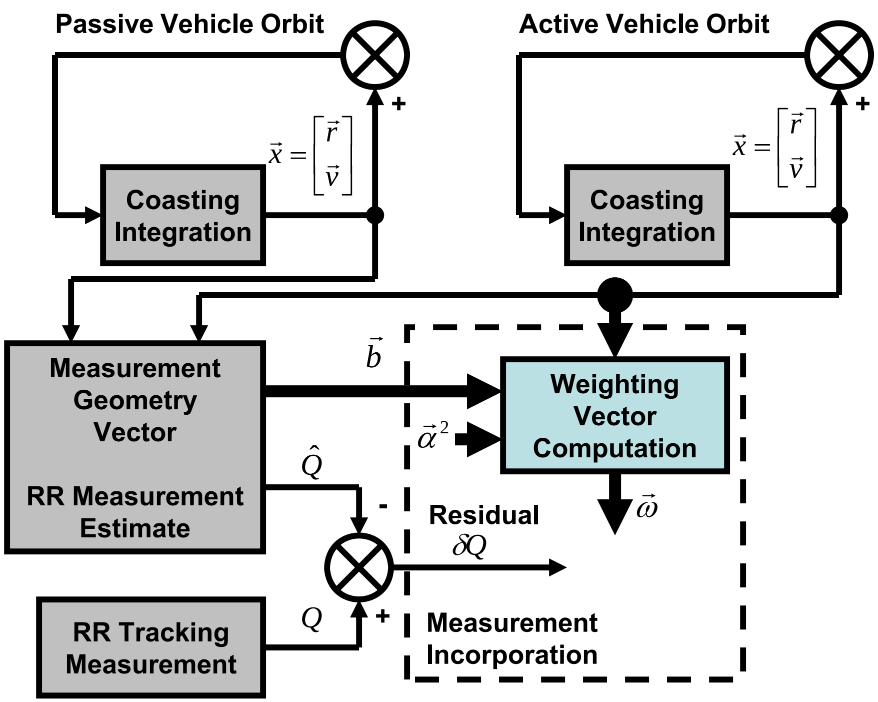
LM Rendezvous Navigation

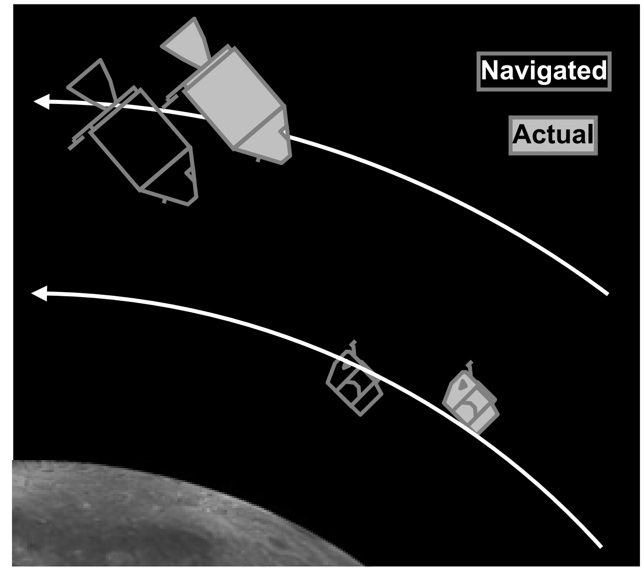




- The navigation software computes an estimate of the RR measurement based on the current state vectors, and a measurement geometry vector
- The navigation software computes the difference (residual) between the actual RR measurement and the estimated measurement

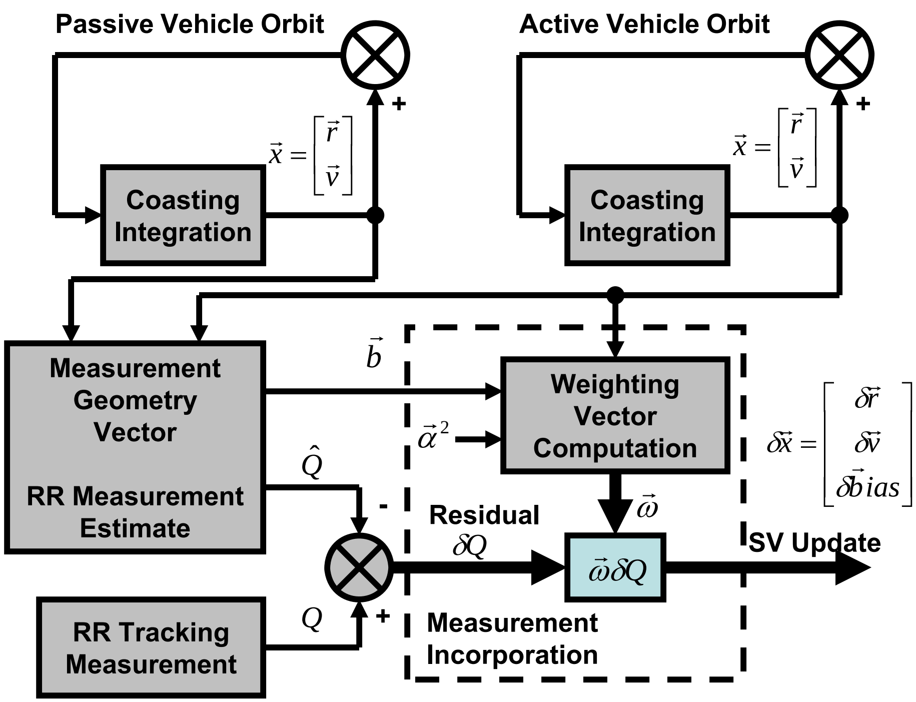
LM Rendezvous Navigation

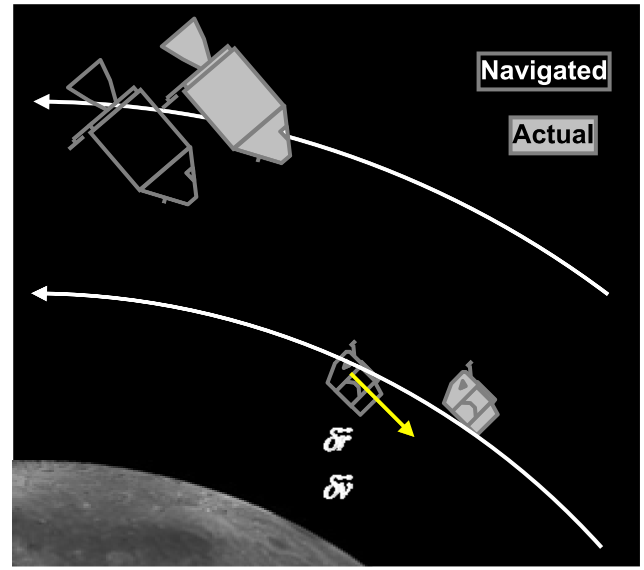




- The navigation software computes a weighting vector based on the current states, the measurement geometry vector, and predefined sensor variances

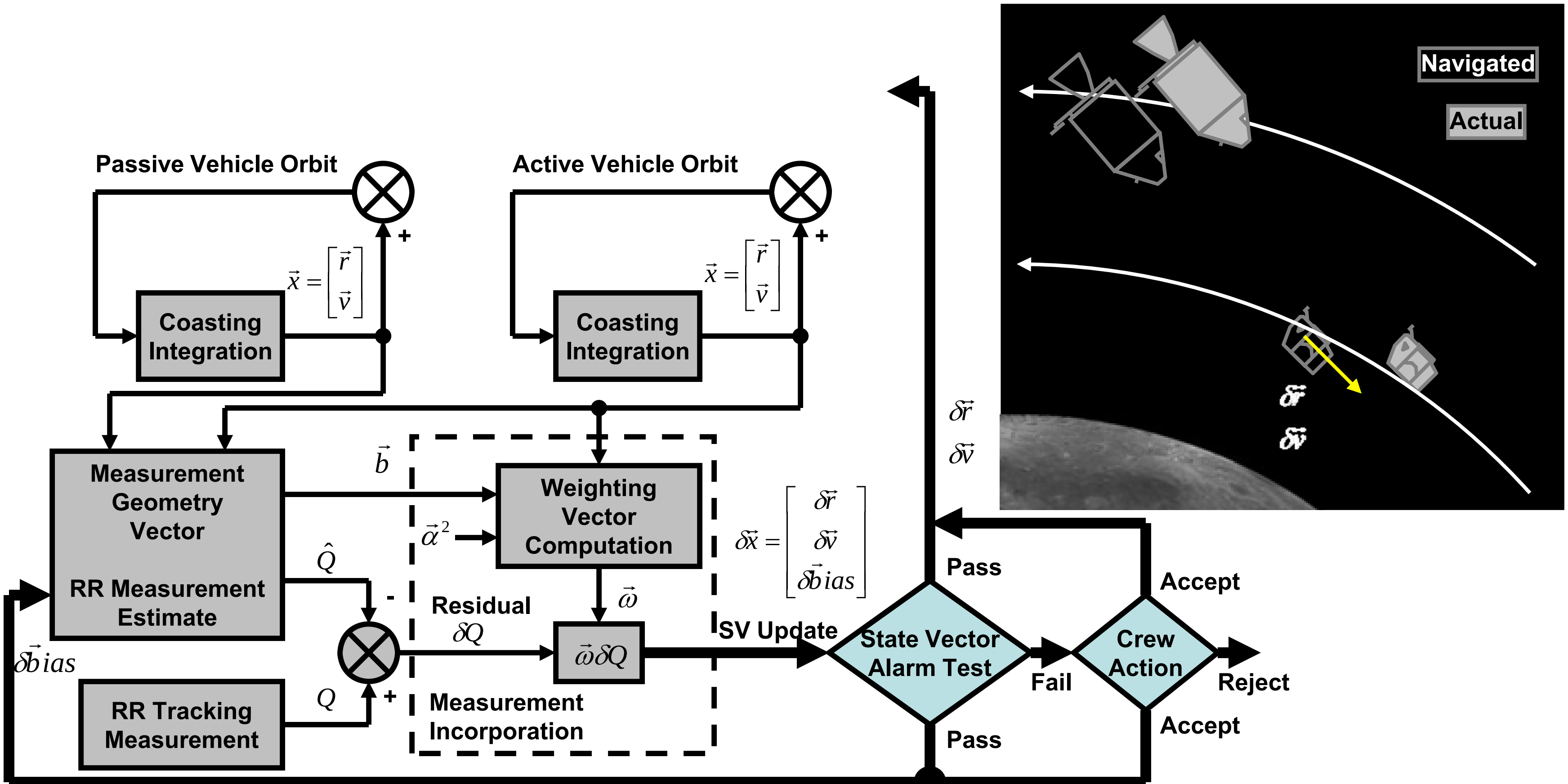
LM Rendezvous Navigation





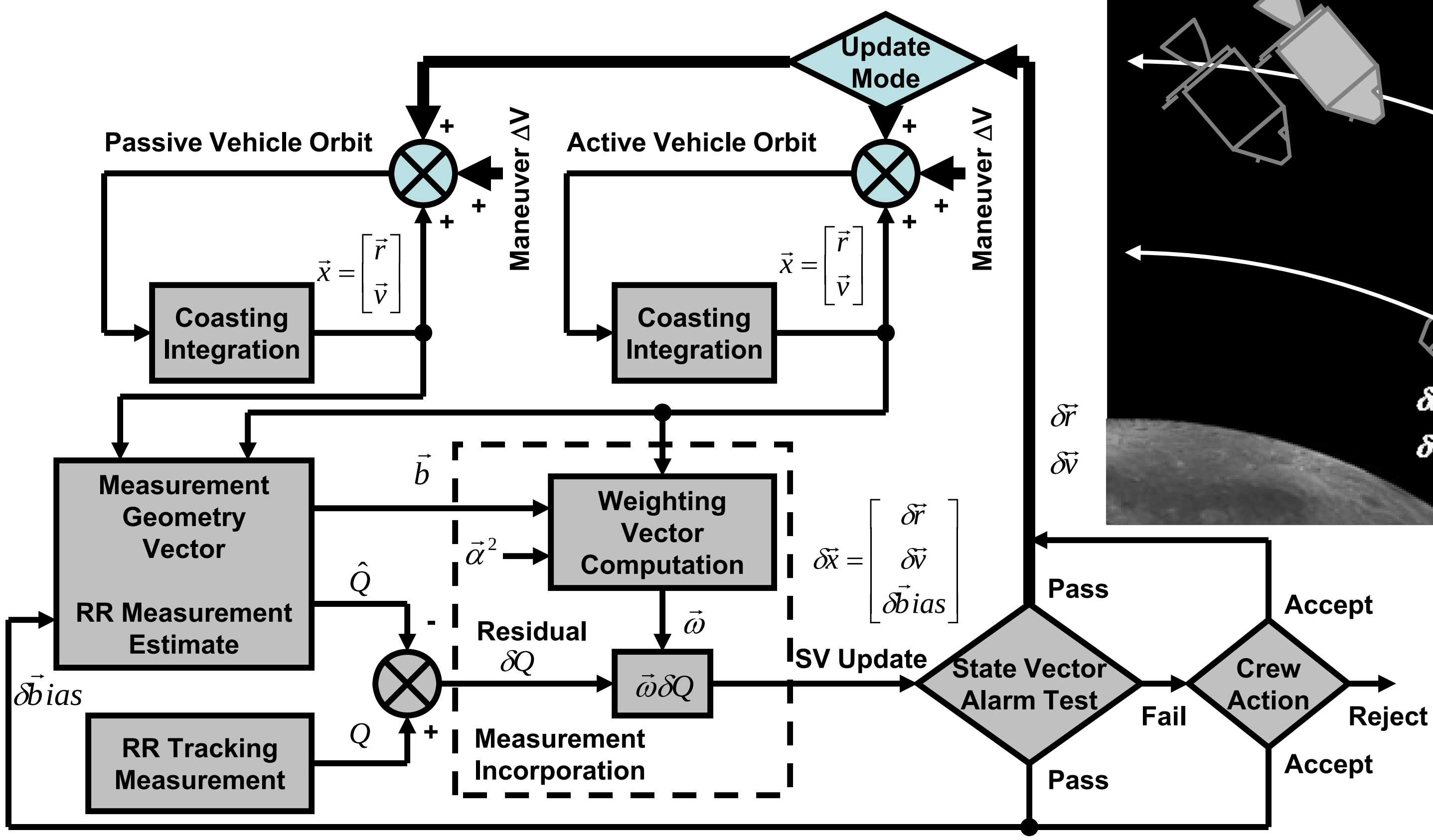
- The navigation software computes an update to the state vector and the estimated RR biases using the weighting vector and the measurement residual

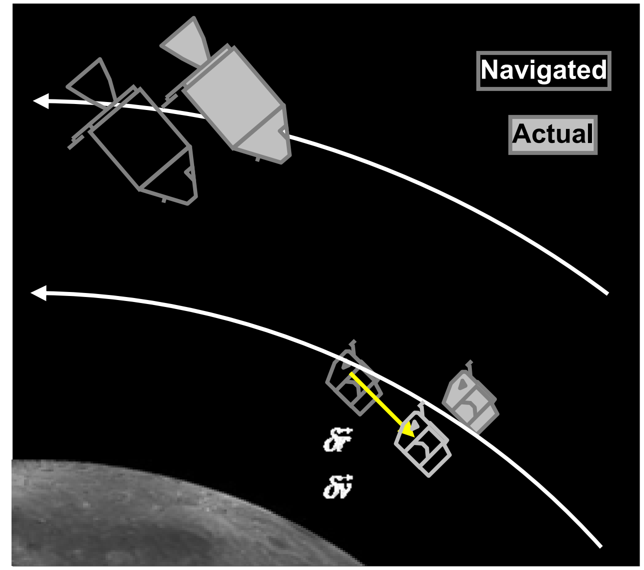
LM Rendezvous Navigation



- The state vector update is tested against a predefined threshold
- If the test passes, the state vector and RR biases are updated
- Otherwise, alarm annunciated and crew either accepts or rejects the update

LM Rendezvous Navigation



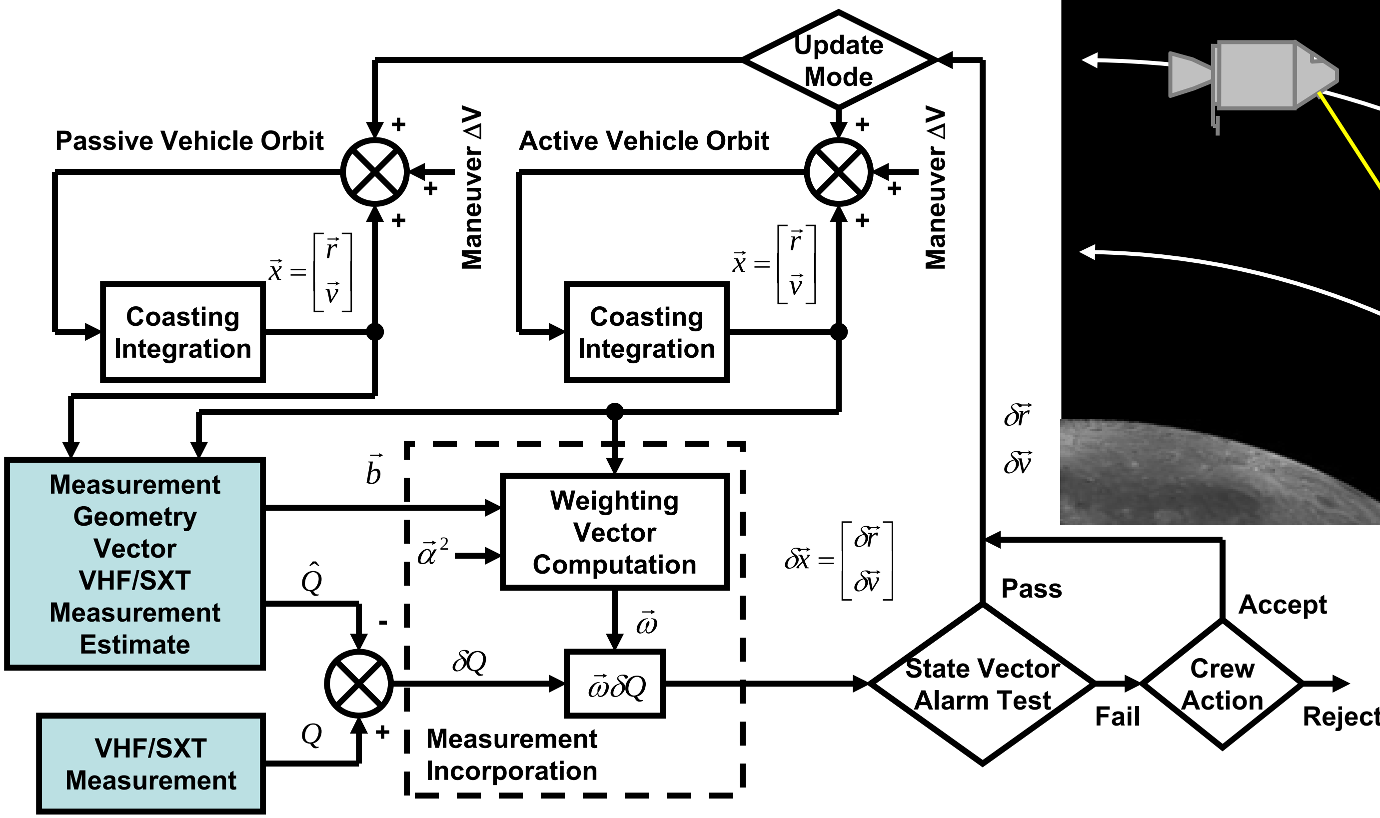


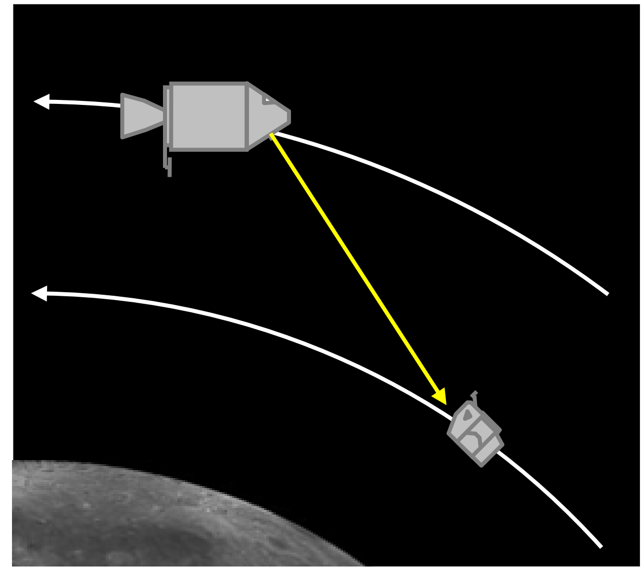
- State vector update can be applied to either vehicle (usually the active vehicle, LM)
- If CSM performs maneuver, maneuver ΔV should be externally applied to CSM vector in the LM to prevent excessive RR updates and improve state vector convergence

If it quacks like one…

- Apollo navigation software initial development by Battin was concurrent with (and independent of) Kalman's work on recursive estimators (later named Kalman filters)
  - Early Apollo documents didn't use Kalman's nomenclature
  - Battin discovered Kalman's work during development
- Apollo navigation software contained several simplifications/differences from "orthodox" Kalman filter
  - W-matrix instead of error covariance matrix
    - Square root of covariance: $[E] = [W][W]^T$
    - Eliminating negative numbers from matrix improved convergence
  - One measurement incorporation at a time
    - Reduced a lot of matrix-vector math to vector-scalar math
  - Measurement edit test used state vector update rather than ratio
    - Ratio test incorporates covariance, becomes more stringent as state vector converges

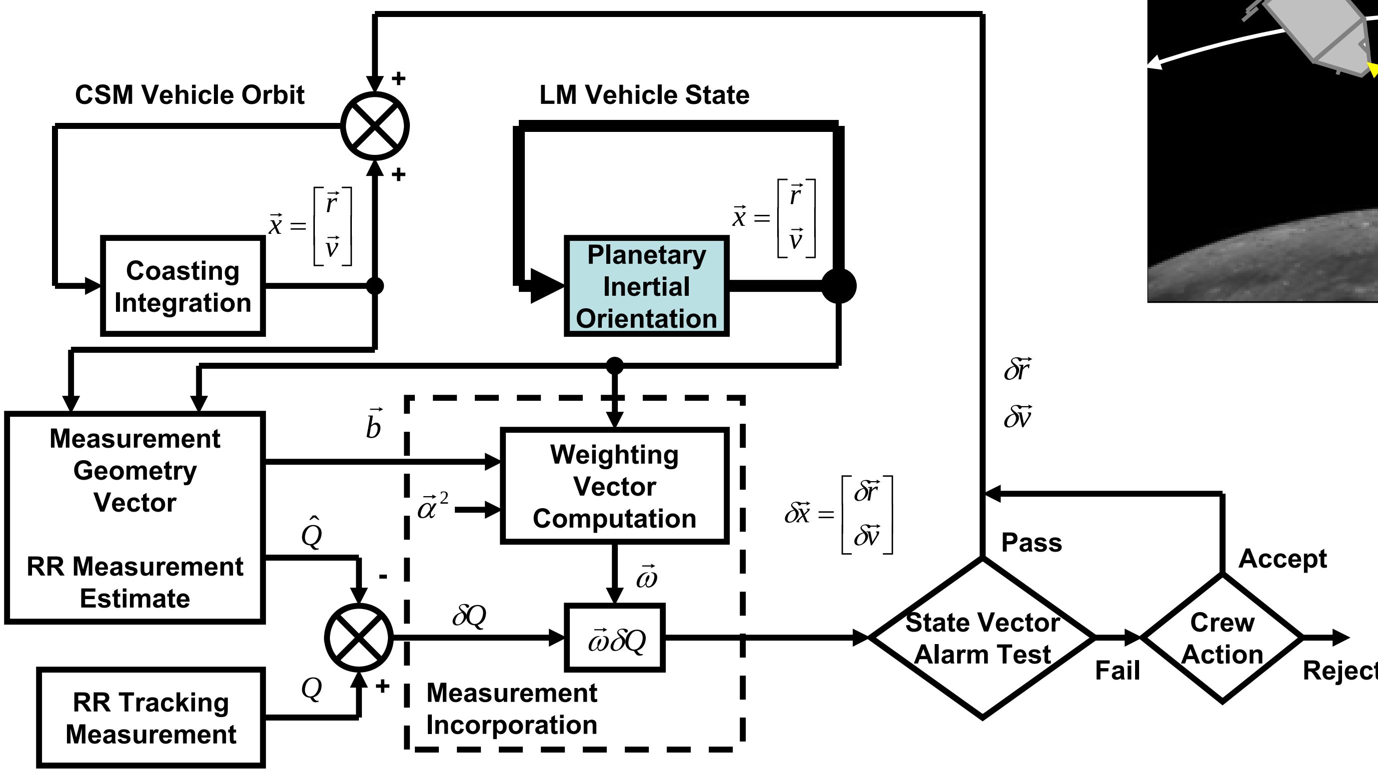
CSM Rendezvous Navigation

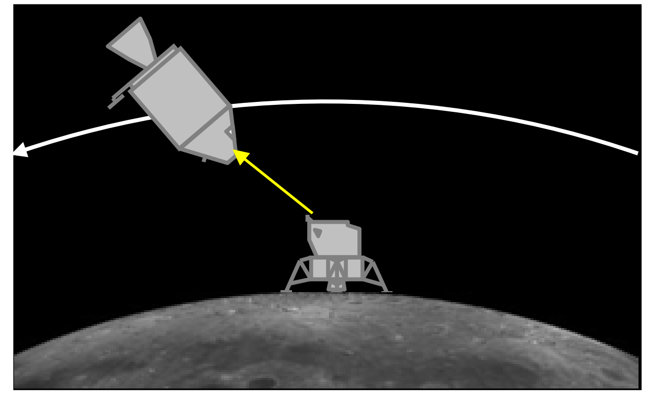




- CSM rendezvous measurements are performed using VHF (range) and SXT (shaft and trunnion angles)
- Sensor biases are not propagated

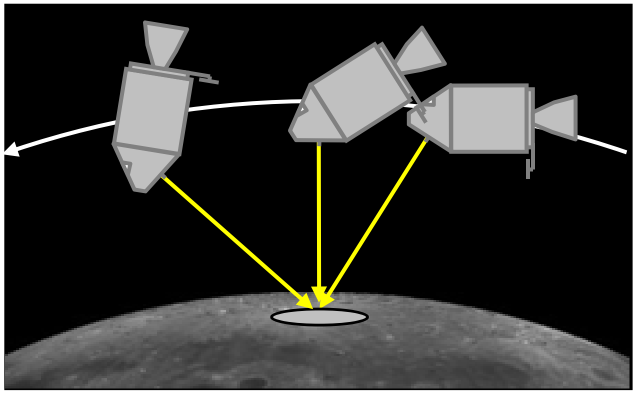
LM Lunar Surface Navigation

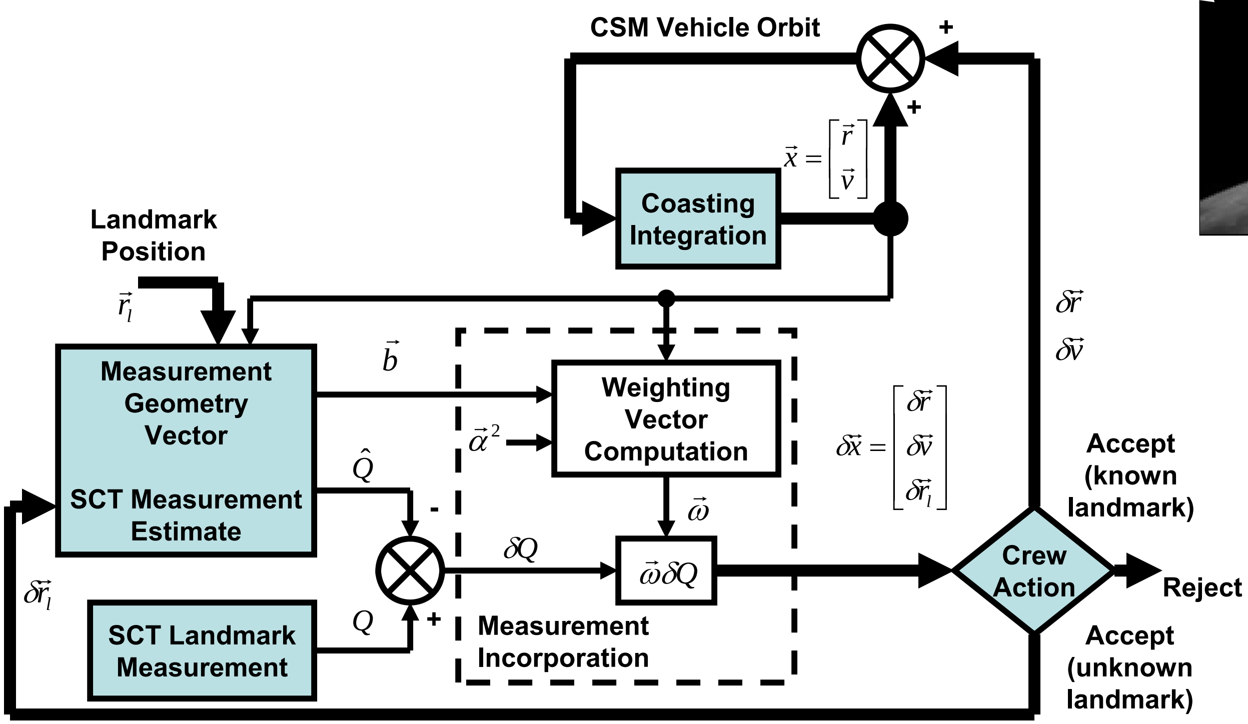




- The LM vehicle state is stored in Moon-Fixed Coordinates and updated by transforming to inertial coordinates
- The CSM state vector is updated using LM RR data
- Only RR range and range rate are incorporated, not angles
- RR biases are not propagated

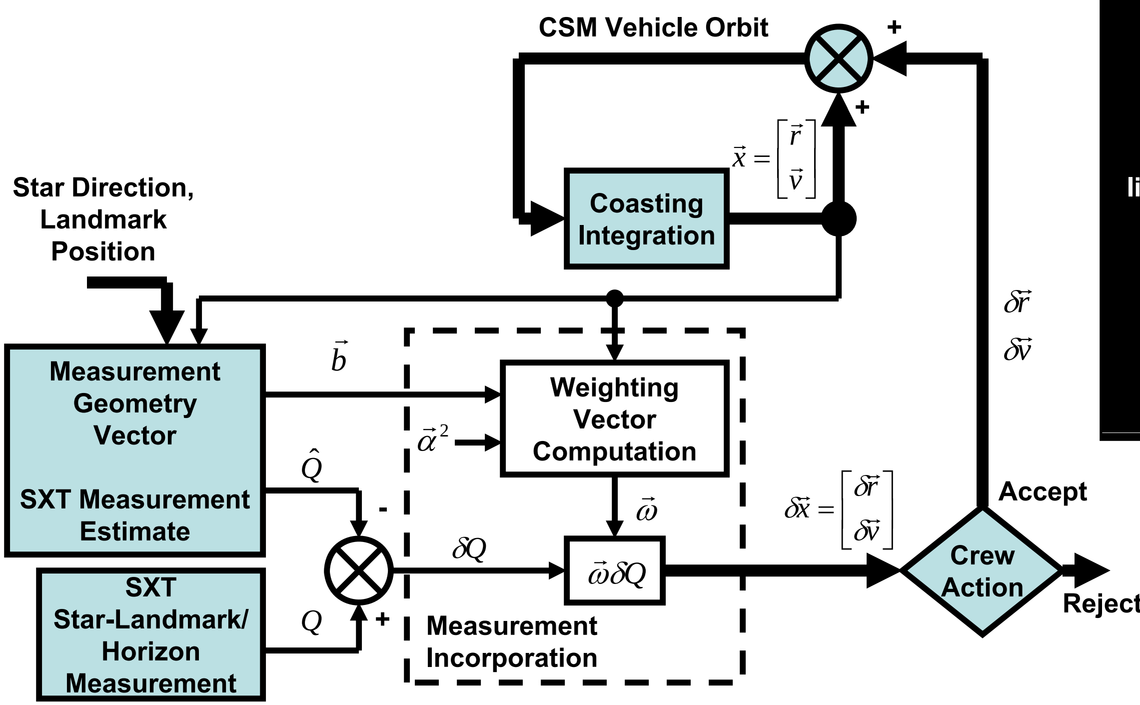
CSM Orbital Navigation

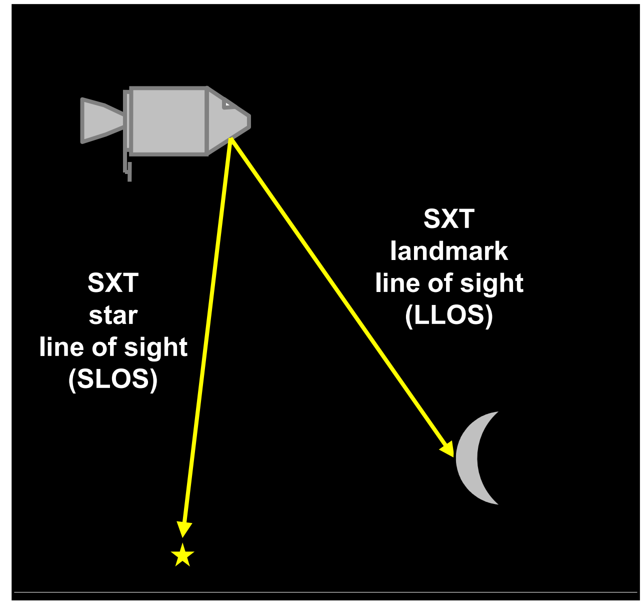


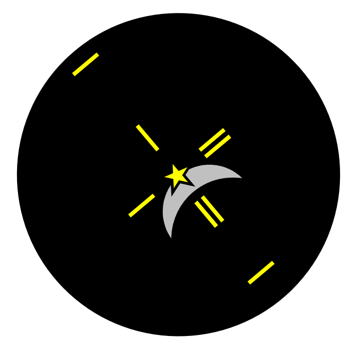


- Only the CSM state vector is propagated
- Measurements are SCT shaft and trunnion angles on a landmark on the Earth or lunar surface
- All updates must be accepted or rejected by the crew
- Landmark may be known (update CSM state vector) or unknown (update landmark position)
- Sensor biases are not propagated

CSM Cislunar-Midcourse Navigation







View through SXT reticle

- Only the CSM state vector is propagated
- Measurements are SXT marks on a star and either a landmark or Earth/moon horizon
- All updates must be accepted or rejected by the crew
- Sensor biases are not propagated

Powered Flight Navigation

- Both CSM and LM used Average-G algorithm for state vector propagation during powered flight
  - Used IMU accumulated ΔV over one guidance cycle (2 seconds)
  - Used average gravitational acceleration over one cycle, primary body only
    - Earth gravity model: spherical and J2 (equatorial bulge) terms only
    - Lunar gravity model: spherical term only
  - Estimated vehicle mass updated based on IMU sensed ΔV
- No measurement incorporation for CSM
- LM Average-G incorporated Landing Radar (LR) measurements only
  - Slant range data available starting at 12.2 km (40 kft) altitude
  - Velocity data available starting at 10.6 km (35 kft) altitude
  - Both range and velocity subjected to simple independent reasonableness checks
  - All data inhibited at 15.2 m (50 ft) altitude
- LM state vector propagated in Stable Member coordinates (rather than Basic Reference coordinates) during powered descent, ascent, and aborts
  - Since IMU aligned to landing/liftoff REFSMMAT, sometimes referred to as landing site coordinates
  - Average-G output transformed back to BRCS for downlink

LM AGS Navigation

- AGS state vectors initialized from PGNS telemetry link upon crew command
- AGS state vectors could also be initialized via manual keyboard entries of vectors voiced up from MCC
- AGS propagated CSM/LM state vectors from last initialized data using acceleration data from ASA
- If LM under PGNS control, AGS acquired rendezvous radar (RR) data (range, range rate, and angles) automatically from PGNS
- If LM under AGS control, AGS acquired rendezvous radar data via manual DEDA entries
  - Range and range rate only
  - Crew manually pointed LM +Z axis at CSM to zero RR angles

Summary

- Review of Basic Navigation Concepts
- Coordinate Systems
- Attitude Determination
  - Prime: PGNCS IMU Management
  - Backup: CSM SCS/LM AGS Attitude Management
- State Vector Determination
  - Prime: PGNCS Coasting Flight Navigation
  - Prime: PGNCS Powered Flight Navigation
  - Backup: LM AGS Navigation

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